Ecological Economics 36 (2001) 165–179

ECOLOGICAL ECONOMICS

www.elsevier.com/locate/ecolecon

ANALYSIS

Entropy and economic processes — physics perspectives

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Received 3 May 1999; received in revised form 30 May 2000; accepted 29 June 2000

Abstract

This paper is a contribution to the discussion on the relation between thermodynamics and economic theory. With respect to thermodynamic constraints on the economy, there are two diametrically opposite positions in this discussion. One claims that the constraints are insignificant ('of no immediate practical importance for modelling') and in the intermediate run, do not limit economic activity and, therefore, need not be incorporated in the economic theory. The other holds that thermodynamics tells us that there are practical limits to materials recycling, which already puts bounds on the economy and, therefore, must be included in the economic models. Using the thermodynamic concept of entropy, we show here that there are fundamental problems with both positions. Even in the long run, entropy production associated with material dissipation need not be a limiting factor for economic development. Abundant energy resources from solar radiation may be used to recover dissipated elements. With simple, quantitative analysis we show that the rate of entropy production caused by human economic activities is very small compared to the continuous natural entropy production in the atmosphere and on the Earth's surface. Further, the societal entropy production is well within the range of natural variation. It is possible to replace part of the natural entropy production with societal entropy production by making use of solar energy. Society consumes resources otherwise available for coming generations. However, future generations need not have less resources available to them than the present generation. Human industrial activities could be transformed into a sustainable system where the more abundant elements are industrially used and recycled, using solar energy as the driving resource. An economic theory, fit to guide industrial society in that development, must not disregard thermodynamics nor must it overstate the consequences of the laws of thermodynamics. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Entropy; Thermodynamic constraints; Solar energy; Radiation; Economics; Natural resources

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PII: S0921-8009(00)00225-1

1. Introduction

Processes in economic systems have important physical aspects that are essential for forming a useful theory. These processes involve conversion of energy and materials and formation as well as breakdown of structure. The conversion processes are of physical necessity dissipative, i.e. they involve production of entropy.

These basic facts form a basis for the magnum opus of Nicholas Georgescu-Roegen, '*The Entropy Law and the Economic Process*', which appeared in print in 1971. This work spawned a multitude of scientific debates and papers as well as increased awareness of the importance of the physical and biological environment for human society. The work was a seminal work for ecological economics. It is most appropriate, now almost 30 years later, to look at this work (in particular) as well as at other related works, in the light of present knowledge and with the critical eye that hindsight can provide. In this vein, the recent reviews of Cleveland and Ruth (1997), Mayumi (1997) and Ayres (1998) discussed subjects of relevance to our topic, although their main emphasis and conclusions fall into other areas.

A main theme in our exposé is the key concept in the book, 'entropy'. We look at it from the perspective of physics/thermodynamics with a view towards the prospects of a long-term sustainable industrial society. The in-depth analysis here will not be presented step-by-step from its physical basis, but in a condensed and comprehensive form. We will underline the idea that entropy is an important concept, but sharing the general limitations of physical concepts when applied in a social context.

We pay particular attention to the significance of the entropy concept in the environmental sciences, including natural resource economics. Here, one is immediately led to the idea of a sustainable, solar-powered society.

In the next section, we point at some particularly important basic facts of the entropy concept and at two errata of Georgescu-Roegen. We then discuss entropy in the context of solar radiation and various aspects of entropy dissipation. The third section is concerned with two entropy-related concepts, negentropy and exergy. In the fourth section, we discuss entropy in societal processes with the focus on physical limits and entropy theories of value. In the fifth section, the prerequisites for a global solar society are discussed on the basis of simple calculations on the entropy balance. Finally, we discuss the implications of our results, in particular in relation to some of Georgescu-Roegen's ideas.

2. Entropy basics

Physicists have discovered a large number of immutable laws of nature. Some of these are particularly important for the social sciences. Foremost among these are the first and second laws of thermodynamics. In the context of societal processes, these may be formulated as

1. Energy is neither consumed nor produced in economic processes
2. Every economic process results in an increase in total entropy

Entropy is often described as a measure of 'disorder'. To prevent a common misunderstanding, we must therefore point out that entropy does not involve the macroscopic 'order' of everyday life. It involves a physical, mainly microscopic, kind of order. Notwithstanding this, entropy is a macroscopic concept in the sense that it cannot be defined for a single or even a few particles, the system has to be large. Denbigh (1981) gives a good exposition of the entropy concepts discussed here, with emphasis on chemical thermodynamics. He also described (ibid. p. 55) a counter-example to the idea that an entropy increase implies an increase of 'disorder'. Technically, entropy is a measure of the distribution of energy among the degrees of freedom (dof) of a system, such that when all energy is concentrated into 1 dof, e.g. as in the kinetic energy of a moving macroscopic body, the entropy is zero. Since the number of degrees of freedom to a certain extent depends on the composition of a system, it is also a measure of compositional order. A system consisting of subsystems, each containing a pure substance, has lower entropy than the same system with all the substances mixed with each other. However, the dependence of entropy on composition is usually very weak. Thus, the entropy reduction when separating a mixture into its components is typically small. Notwithstanding this rule of thumb, there can in some cases be quite substantial amounts of energy in concentration gradients. As an example, when the freshwater of a river mixes with seawater, under the ideal solution assumption, it can be shown that the entropy of mixing involved is such that the energy dissipated corresponds to the river going through a fall >100 m high (Pattle, 1955).

2.1. Two entropy-related errata of Georgescu-Roegen

The first error concerns the division into material and energy entropy, which Georgescu-Roegen used extensively and in particular in his 'fourth law' suggestion. The division is fallacious. There is only one kind of entropy, irrespective of whether the physical system is material or immaterial. In particular, entropy is carried by electromagnetic radiation (zero mass photons). There are some differences in the entropy formalism and derivations that, for some ideal cases (e.g. photon gas, ideal gas), makes a distinction between material- and energy-carried entropy useful, but it must be kept in mind that what is discussed is actually one concept. In particular, when a system has both immaterial and material components that interact, as is the case for all systems on the Earth, the distinction easily leads to fallacious conclusions; see, e.g. Månsson (1994) and references cited therein.

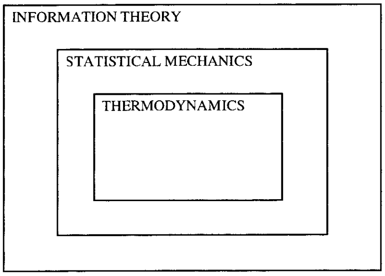

Fig. 1. The phenomenological thermodynamics is embedded in the theory of statistical mechanics. With statistical mechanics, it is not only possible to explain and derive the results of thermodynamics, but also to treat some effects that thermodynamics cannot handle. For example, this applies to many systems in which quantum-mechanical effects are important. However, there are still some open problems in statistical mechanics. One appropriate framework for treating these is the mathematical theory called information theory, which can be connected to statistical mechanics (Jaynes, 1957, 1963, 1983). Information theory can, for example, quantitatively describe structure formation processes (Eriksson and Lindgren, 1987; Lindgren, 1987, 1988; Månsson and Lindgren, 1990).

The second error concerns the connection between statistical mechanics and classical thermodynamics. Georgescu-Roegen spent considerable effort on investigating this connection, pointing out the problems arising through the use of classical mechanics for describing the dynamics. Apparently, the difficulties associated with reconciling the mechanical (deterministic–entropy production impossible) approach with the probabilistic (random or non-deterministic) statistical approaches lead him to dismiss statistical mechanics. These difficulties remain, but in a physics perspective they are not sufficient reason to dismiss a theory of such proven usefulness until a superior theory, capable of resolving the difficulties, is developed. In particular, there are a number of phenomena that can only be satisfactorily treated with statistical mechanics — photon entropy is one example (Fig. 1).

2.2. Entropy and solar radiation

Since solar energy, i.e. electromagnetic radiation, is a central theme of this paper, it is necessary to discuss the entropy of such radiation in some detail. For an extensive treatment, see Landsberg (1978), chapter 13. The key factor determining the entropy is how the energy of the radiation is distributed over frequencies, i.e. the energy spectrum. The benchmark case is so-called blackbody radiation, which is (somewhat imprecisely, see Landsberg (1978)) the spectrum of the emission from a perfect black body, e.g. a piece of matter that absorbs and emits at all frequencies equally well. The spectrum is then only dependent on the temperature T of the body. The emission, P, is then given by Stefan–Boltzmann's law

$$P = \sigma T^4 \text{ W/m}^2, \quad (1)$$

where $\sigma = 5.6710 \times 10^{-8}$ W/m^2 K^4 is Stefan–Boltzmann's constant. The entropy per unit volume of (isotropic) blackbody radiation can be written as

$$S = \alpha T^3 \quad (2)$$

where α is a constant involving Planck's constant, Boltzmann's constant and the vacuum velocity of light.

Blackbody radiation corresponds to the largest entropy of radiation of given volume and energy. Neither the incoming solar radiation nor the outgoing radiation from the Earth is quite blackbody. This means that there is a potential in the outgoing radiation for some further entropy production before the equilibrium, blackbody, is reached. In practice, however, this potential is small. Likewise, the correction due to non-isotropy of the radiation is small. The important potential is due to the different (effective) temperatures of the solar (≈ 5760 K) and Earth (≈ 278 K) radiation. Since the amounts of in-going and out-going energy are, to a very good approximation, equal, insertion of these temperatures in Eq. (1) and Eq. (2) yields the entropy flow difference, which corresponds to the amount of entropy produced on the Earth.

2.3. Processes always involve production of entropy

In thermodynamic theory, there is one exception to the rule set out in the heading. It is the set of ideal processes that run in a so-called thermodynamic equilibrium. Equilibrium is a particular state where all thermodynamic forces (e.g. differences in temperature, pressure and concentration) are balanced and in which the entropy is maximal. In classical thermodynamics, this is a state in which the macroscopic state variables are constant if the system is left to itself.

Although the macroscopic state variables are constant in equilibrium, many micro-scale processes are going on — energy is exchanged between molecules via collisions or photons, etc. Since the entropy is constant, already at its maximum, these processes do not produce entropy. Lindgren (1988) discussed how such microscopic processes lead to production of entropy in a non-equilibrium situation.

So-called ideal processes, taking place at equilibrium, do not produce entropy. Physically, this implies that changes in macroscopic state variables must be very slow. In the classical thermodynamics picture, one should actually speak about close-to-equilibrium processes, since, in a strict sense, equilibrium processes are impossible: at a macroscopic level no thermodynamic change can occur in the system when all thermodynamic forces are balanced. Clearly, these are idealised processes, never to be observed in nature. In fact, many processes in nature run far from the thermodynamic ideal where entropy production is zero and practically all physical processes in the economy are far from thermodynamic equilibrium. Some processes cannot even, in principle, run close to equilibrium.

It is, indeed, very difficult to identify a process in the physical world running without any kind of thermodynamic loss, i.e. without entropy production. On the macrocosmic scale, one may think of two bodies in space, both in radiation balance with the background radiation, revolving around each other; however, since gravitational attraction has infinite range, any system may interact with the rest of the universe so that entropy is produced. On the microcosmic scale, it may be argued that an electron in an atom, while moving in a certain state, does not produce any entropy. However, the infinite range of interaction and the additional consequences of the uncertainty principle imply problems also for this process. In the light of these difficulties, we offer the tentative hypothesis that there are no processes that run without thermodynamic losses. All such losses may be expressed in terms of entropy (entropy production), albeit in most cases such a description is significantly incomplete.

In the particular case of an isolated system, i.e. a system with no exchange of matter or energy with the outside world, the second law says that the entropy of the system will spontaneously increase until it reaches its maximum (equilibrium) value. For all non-isolated systems, the entropy of the system may increase or decrease with time. Thus, one must warn for a possible and common misunderstanding of the second law: that the entropy of a particular subsystem in the economy/society must increase. The truth is that there may be subsystems for which this is not the case. As we show below, it may well be that the entropy will decrease for the human society as a whole. Even if there is entropy production in a particular system, that system may export the produced entropy to other systems, keeping its own entropy constant; it may even decrease its own entropy in this way (e.g. a refrigerator). However, in accordance with the second law, the entropy of the total, isolated system (system plus surroundings with appropriately chosen boundaries) must increase in the process. Georgescu-Roegen (1970), (p. 55) observed that: “The entropy of copper metal is lower than the entropy of the ore from which it was refined, but this does not mean that man’s *economic* activity eludes the Entropy Law. The refining of the ore causes a more than compensating increase in the entropy of the surroundings”.

Using copper as the example implies a rare problem of interpretation as copper often appears as a sulphide. If the sulphur is assumed to be oxidised, the process of producing metallic copper from the ore is accompanied by a strongly exothermal process.

However, for most metals and ores, the interpretation of the statement is straightforward. Following the metal somewhat further, it is at present typically to a large extent dissipated in use (as well as deposited in nature), so that it ends up in a state with higher entropy than in the original ore. However, with appropriate technology and social organisation, it is possible to slow down or even to reverse such dissipation processes, thereby building up stocks of low entropy material in society while exporting the corresponding entropy from the Earth. Today, such stocks are mainly built up in the form of aluminium or steel, but the amounts are small.

Another example is the set of biological processes through which carbon dioxide and water are turned into carbohydrates in food, which is then in several steps consumed, returning to carbon dioxide and water. Although the energy flows in this set strictly speaking form a web, it has been customary to talk about it as a food chain, not a food web. The entropy content of the organisms in the whole chain is practically constant, although all links in the chain involve entropy production — also in this case, the produced entropy is exported from the Earth.

Given that entropy production occurs in non-equilibrium systems, one should note that the entropy concept is often regarded as problematic in non-equilibrium, open systems. One main reason is that there is an intractable measurement problem, i.e. that it can be very difficult to find a unique value for the entropy. Most thermodynamic measurements are based on establishing equilibrium between measurement apparatus and the system being measured, e.g. as when measuring temperature with a thermometer. The first question is then, what constitutes equilibrium between an equilibrium and a non-equilibrium system. (A non-equilibrium system may not have a unique temperature — it may well have several distinct ‘temperatures’ or even a continuous spectrum.) If, furthermore, the system is open, it may be changing its state continuously — in any case, the entropy value will be influenced by the exchange with the surroundings. However, note that formally, the entropy can be well defined also for non-equilibrium systems, e.g. using the information–theoretical basis of statistical mechanics and thermodynamics.

It has been suggested that non-equilibrium systems evolve so that the entropy production is minimised (Nicolis and Prigogine, 1977). Since the argument is based on an assumption of ‘local thermodynamic equilibrium,’ the minimum entropy production principle has not been shown to be valid far from equilibrium. There are even systems for which the local thermodynamic equilibrium assumption is valid, but for which the principle does not hold (Månsson, 1985). In fact, the second law is the only entropy-related evolutionary principle which is known to be generally valid.

2.4. Entropy in throughput and cyclical processes

Ideal processes can be put together into cycles transforming matter and energy in a loss-free way, as the famous Carnot cycle (which is described in virtually all thermodynamics textbooks, e.g. Haywood (1980), Modell and Reid (1983), Van Wylen et al. (1994)) transforms heat into work. Thus, they can in principle be run back and forth forever. Real systems are different; they are non-cyclical in the sense that a certain throughput is necessary and entropy is produced.

Ecological systems are often described as systems that use matter in a cyclical or loss-free way. There is an element of truth in this — ecological systems function in ways that counteract losses of some elements. However, carbon, oxygen, nitrogen and hydrogen are released from the ecosystem to the atmosphere and then recollected. Dissipative, entropy producing processes perform the ecological re-circulation of matter.

Electromagnetic radiation is a particularly important case of non-circular flow in ecosystems. In addition to the incoming and outgoing radiative energy flows, there is energy in other forms such as sensible and latent heat, chemical energy and radiation. Parts of the transformations between the different energy forms involve radiation. The radiative flows of energy may be regarded as ‘circulating,’ in the sense that photons are exchanged back and forth among the components of the ecosystem. The overall result is that the spectral distribution changes so that the entropy of the radiation increases; the incoming low entropy solar radiation is step-by-step transformed into outgoing high entropy heat radiation.

The solar-driven ordering (entropy reduction) performed by biological organisms is not the only kind of ordering process on the Earth. On geological time-scales, materials are changed and concentrated (entropy reduced) through geophysical processes, some of which are not driven by solar energy, such as the circulation within the Earth driven by heat from radioactive decay. In such cases, different geophysical forces, e.g. temperature gradients and gravitation, act upon differences in density and physical and chemical properties (Hedenquist and Lowenstern, 1994). In these cases, the entropy reduction is very small compared to the entropy produced as energy bound in decaying nuclei is transformed into heat.

In some cases, or to some extent, materials lost to the ecological systems are brought back into circulation by geophysical processes. Some of these are extremely slow — some of the materials locked into sediments at the bottom of the sea are eventually returned to land by volcanic action at the subduction zones. In the case of carbon, however, man’s burning of fossil fuels is an enormous speed-up of the geophysical re-circulation. However, most of the damage caused by the releases of carbon and sulphur into the atmosphere is unrelated to the entropy produced. In other cases, the geophysical part of the circulation is relatively short-lived: oxygen from the atmosphere is bound into water and carbon dioxide, which is given off to the atmo- and hydrosphere. The carbon dioxide is taken up by plants, which release oxygen. Note that in this circulation, the dominant factor in entropy terms is the one due to chemical reactions, not the entropy of mixing associated with the various processes.

3. Other key concepts in thermodynamics

Since entropy has been put forward as a basic physical resource concept or even measure, it is sensible to take a look at some other physical resource concepts, e.g. in order to compare the relative effectiveness as a resource measure. We will bring forward two such concepts: negentropy and exergy.

3.1. Negentropy

For any system, there is an upper limit to the amount of entropy it can contain under specific conditions. The difference between this maximum and the actual amount of entropy in the system has been given the name ‘negentropy’. To determine the negentropy, one first has to determine the entropy and calculate the maximum entropy. Since the determination of these two entities provides most of the thermodynamic properties of the system, and since their difference adds nothing to the knowledge about the system, we regard negentropy as a concept of very limited usefulness for thermodynamics proper. Its use lies mainly in shortening the notation in some derivations — but the effect is, in our view, not sufficiently large to motivate the introduction of an additional concept in the thermodynamic theory.

However, in some thermodynamic applications use of the negentropy concept eliminates the necessity of performing laborious integrations from a zero Kelvin reference state. As we will see below, negentropy is also a handy concept in discussions of physical resource use, i.e. as a physical resource measure. This is mainly due to the fact that negentropy is a complementary concept to entropy. Here, it is important that negentropy may increase in a particular system only if entropy is produced somewhere else. When negentropy in a particular system is consumed, entropy may be reduced in another system — but it is not necessarily so.

3.2. Exergy

Of the two basic laws of thermodynamics, the first has its focus on energy, the second on entropy. Practically from the first formulations of these two laws in the 19th century, there have been attempts to combine the two carrying concepts into one. The successful efforts in this direction have been based on the notion of the entropy-free part of the energy — that is the part of the energy which, using ideal processes, could be completely transformed into mechanical energy (work). Mechanical energy plays a key role in thermodynamics since it is directly connected to fundamental physical entities, in particular mass and velocity, and since it is a form of energy with zero entropy (all energy in 1 dof). The latter implies that the energy can be completely converted into any other form of energy.

This concept was given many names, including ‘useful energy’, ‘available energy’ and ‘availability’. Eventually, it was agreed to follow the suggestion of Rant (1956) on the term ‘exergy’, which has appropriate linguistic roots (being a combination of Greek syllables meaning ‘out of’ and ‘work’) and can be expressed in many languages with ease.

Exergy, then, can be expressed as the maximum amount of useful energy one can get out of a certain system, given specified conditions. Since the exergy is calculated under freedom from process constraints other than ideality, exergy is essentially a generalisation of the common free energy concepts of physics and chemistry (Szargut et al., 1988). These may be defined as: “Free energy is that energy which can be transformed into mechanical work” (Georgescu-Roegen 1971, p. 129), provided one adds the processes are ideal (no entropy produced) and a specification of the restriction that applies for the particular kind of system; e.g. if the system is at constant temperature and pressure one gets the ‘Gibbs free energy’ concept, which is commonly used in chemistry. Exergy is often what laypersons mean when they talk about energy.

Exergy cannot be created, only destroyed. Exergy is, therefore, a physically limited (scarce) resource, which is furthermore a necessary input in any economic process (cf. Koopmans 1973, p. 250). When put in these terms, it is clear that the study of the optimal use of exergy falls at least in part within the realm of economics.

There is one exception to the rule that exergy cannot be created. In the early expanding (‘Big Bang’) Universe, in which the expansion led to a rapidly changing equilibrium state, the rates of the equilibrating processes were too low to keep up with the change. So there was a period within the initial phase of the big bang where the gap between the actual and the equilibrium state widened and, therefore, the exergy of the universe was actually increasing (Eriksson et al., 1982). This is the exergy we are living from today.

There is a direct relation between free energy and entropy — roughly speaking, a system contains more free energy when its entropy is low than when it is high, and when the entropy is maximal there is no free energy within the system.

For the special case of blackbody radiation of temperature T, the exergy E can be expressed in a simple form,

$$E = U\left[1 - \frac{4}{3}\frac{T_{\mathrm{r}}}{T} + \frac{1}{3}\left(\frac{T_{\mathrm{r}}}{T}\right)^{4}\right] \tag{3}$$

where T_r ($\leq T$) is a reference temperature (e.g. the temperature of a cold reservoir) and U is the energy flow rate. It is also possible to calculate the exergy for non-blackbody radiation (see Karlsson, 1982; Eriksson and Lindgren, 1987 pp. 59–63), but such expressions are more complicated.

The expression in the brackets in Eq. (3) corresponds to a theoretical upper limit to the efficiency of solar energy conversion devices. Note that this is less than the Carnot efficiency. One way of understanding why this is so is to note that whereas the heat flows in an ideal Carnot engine are one-way, a radiative energy exchange must always be two-way, since a body must emit and absorb equally well at any given frequency. Inserting the effective blackbody temperatures of the Sun and the Earth in Eq. (3) yields 0.936. One should note here that the use of an average Earth temperature is problematic. It does matter that there are temperature differences over the Earth's surface — using the average temperature means that the potential is underestimated.

It may well be argued that the correct reference temperature to be used in this calculation is the cosmic background radiation, ≈ 3 K. There is some justification for this claim. It is technically possible to achieve radiative interaction between systems on the Earth's surface and the empty space that partly bypasses the atmosphere. These are very special cases indeed, but of some practical relevance; see, e.g. Granqvist (1991).

4. Entropy in societal processes

Georgescu-Roegen repeatedly pointed out that the standard economics thought treated the economic system as completely circular and self-sustaining, e.g. as interaction between consumption and production within a completely closed system (Georgescu-Roegen, 1970). In fact, one of the most important contributions of Georgescu-Roegen was his attempt to change the systems view of economics from this conventional (monetary) circular to the (partly physical) throughput one (Daly, 1995), thereby bringing economists and economics back towards reality. In particular, whereas the conventional models of the economic system were without connection to the physical world and thereby unconstrained by the laws applying there, the models with the economy as a throughput system have considerably less freedom of action, implementing some of the physical and other constraints that apply in society. There are a number of essential questions that automatically arise within the latter view (Ayres and Kneese, 1969; Ayres and Kneese 1989; Ayres and Nair 1984). Paramount amongst these is what physical/biological limits there are to the scale of the economic system/process (equivalently, what are the physical limits that set upper bounds to growth processes), an issue repeatedly stressed by Daly (1979, 1985, 1987) and others.

4.1. Entropy-related physical limits

In terms of entropy, the two most important physical limits are local over-heating due to limited entropy export capacity and the minimum entropy reduction requirement for concentration of very dispersed materials. The first may be a problem for the local environment around power plants and in cities. For the Earth as a whole, the limit on the rate of entropy export is inessential (see below).

Physical laws also have a number of important consequences for industrial production processes. The discussions on long-term sustainability have shown that it is no longer sufficient to regard only monetary costs and supply/demand relationships in an economic analysis; the thermodynamic constraints on the involved energy and material transformations must also be considered.

Georgescu-Roegen (1970, p. 54) stated that, "From the viewpoint of thermodynamics, matter-energy enters the economic process in a state of *low entropy* and comes out of it in a state of *high entropy*". This is not entirely correct. There are many physical inputs to the economic process with high entropy, e.g. metal in ores have higher entropy than the refined, useful metal; seawater used for desalinisation and air used in combustion processes. There are also situations with matter and energy leaving the economic process with low entropy, e.g. in waste deposits. In this case, the potential for entropy production may be utilised by natural systems. These exceptions to the rule formulated by Georgescu-Roegen invalidate the view that the build-up of low entropy can be regarded as a description — still less a goal — of the economic process.

We noted above that according to our judgement, there is very little build-up of low entropy material stocks on the Earth in comparison with the entropy produced. This is due partly to our use of materials in their natural forms, i.e. without changing their entropy — the dominant material use is sand and stones used as building materials. Partly it is due to the multitude of dissipative energy uses, in which no low entropy material stock is built up at all. Using fossil fuels to produce a car results in a net decrease of the global stock. Driving it will decrease the stock even more; corrosion and wear will eventually destroy the car.

In a steady state economy, the dissipation of capital stocks has to be compensated for; for growth, there must be an extra addition. This raises the question how much negentropy is needed for this compensation. This is not known since just as there are no reliable quantitative estimates of the stock size, there is none of the dissipation rate (note that it is much easier to calculate the addition to the negentropy stock). When the dissipation of the capital stocks is taken into account in macroeconomic models, the dissipation rate is typically assumed to be proportional to stock size. This practice may be due to the fact that in some simple, well-known physical systems, dissipation is proportional to 'stock size.' However, this kind of simple relationship is exception rather than rule.

At present, however, even those societal processes that do result in a build-up of low entropy stocks typically have such a low thermodynamic efficiency that the production of entropy is many times the entropy reduction of the added capital stock.

4.2. Entropy and value

All processes governed by humans produce entropy. We cannot start processes if the entropy is at its maximum. Therefore, physical resources in the form of low entropy, or high exergy, are vital instruments for running desired processes. Clearly then, such physical resources are expected to have instrumental value. Unfortunately, this instrumental value cannot be measured in entropy terms, since a necessary prerequisite for such a measure is that all thermodynamically possible processes are available.

The entropy would serve as a general measure of instrumental value, assigning unique values to each resource, only if all transformation processes had the same losses or efficiency; or preferably, all processes were ideal. However, as mentioned above, there are intrinsic physical limits for some processes, different for different processes — this difficulty could only be overcome by eliminating all such processes from the economy. Furthermore, in real life there are technological limits and constraints, also different from process to process — this difficulty could in theory be overcome by technological skill, in the real world technological development is not aimed at and does not result in a common level of efficiency.

Georgescu-Roegen discussed the relationship between entropy and value in many of his works, e.g. in 'Energy and Economic Myths' where he states: "…what goes into the economic process represents *valuable natural resources* and what is thrown out of it is *valueless waste*" (1970, p. 53); he then continues with the quote above (*op. cit.*).

Taken together it is true that the 'matter-energy' enters the economic process in a state of lower entropy than the state at which it leaves. This is a necessary consequence of the second law. As pointed out above, this does not necessarily hold for any specific type of matter. Low entropy may be in a form that we do not have any technology to utilise and it may be left in its state of low entropy. There may be other costs associated with the utilisation that make the physical resource of a low entropy material economically without value.

One may interpret Georgescu-Roegen's statements about low entropy in solar radiation as one example where he thought that was the case. He is acknowledging that low entropy is not sufficient for something to be valuable and says: "Low entropy, as I have stated earlier, is a *necessary* condition for a thing to have value. This condition, however, is not also *sufficient*" (Georgescu-Roegen 1971, p. 282).

However, such statements on 'low entropy' are difficult to discuss, as there is no natural reference scale for entropy. An economic process typically brings together production factors producing a set of products with a greater market value than the value of the inputs. That process will have produced entropy. Thus, the more valuable products and waste materials, taken together, will have greater entropy than the total entropy of the less valuable inputs. The point is, of course, that the economic value resides in only part of the output, but when discussing entropy it is incorrect to take only this part into account.

There are many examples of things with higher entropy having greater value. Georgescu-Roegen himself presents as an example that a person may prefer an omelette to an intact egg. In this case, the difference in value arises as a consequence of personal taste. Another example is an edible mushroom, which may have higher entropy but be more valuable than a poisonous one. This difference in value is set by the human physiology. And as stated above, because there are no technologies available, some forms of low entropy lack instrumental value.

In addition, the first part of Georgescu-Roegen's statement, where he says that low entropy is a 'necessary' condition for a thing to have value, may well be questioned. As illustrated above, lower entropy does not necessarily mean greater value. What, then, could low entropy as a necessary condition for being of value imply? If low entropy is anything but maximum entropy then almost everything would qualify as the Earth is not in equilibrium. But, one may even find examples where maximum entropy is desired — when painting a wall it is normally desired to have the same colour over the whole surface. Therefore, paint is more valuable if the pigments and solvents are distributed homogeneously, i.e. with maximum entropy of mixing within the total volume of paint.

These examples illustrate that it is difficult to defend any general, meaningful statement on the relation between entropy and value. Human desires and what technologies happen to be available for humans to fulfil these desires are important factors overriding the thermodynamic criteria of what constitutes physical resources. Georgescu-Roegen was clearly aware of these problems when writing his 1971 book: "Without the concepts of *purposive activity* and *enjoyment of life* we cannot be in the economic world. And neither of these concepts corresponds to an attribute of elementary matter or is expressible in terms of physical variables" (1971, p. 282).

Also, in the cases that can be addressed with the methods of physics there are complicated relationships. The environmental problems connected to materials are often not adequately described in terms of entropy or similar concepts — it is more often related to what may be called the 'toxicity' (in a wide sense) of the materials. A key point is whether or not materials are present in useful forms; this is not determined by their entropy. Going beyond the entropy concepts, we may note that the usefulness of matter/energy is only partly and in a certain sense described by exergy. For any description in exergy terms, it is not enough to specify the physical measure of instrumental value that the exergy concept contains. It must also be considered for whom a particular amount of exergy represents an instrumental value and for what purpose whomsoever is using the exergy. In conclusion, in almost all cases a purely physical description is fundamentally incomplete. The complications lie not only in the physically not so simple inputs and outputs, but also in the non-physical, mainly social, aspects of value, cf. Kåberger (1991).

On the other hand, a description without any physical element is almost certainly misleading. In many cases, e.g. for most industrial processes, a description in physical terms is absolutely necessary and a purely economic description is completely useless. A physical description of economic processes yields information on where the limits are and on what is possible to do (Berry et al., 1978; Berry and Andresen, 1982; Månsson, 1986, 1990).

5. The earth's entropy balance and a solar society

The difference in entropy of the incoming solar energy and the outgoing radiative heat flow constitutes a natural resource (a potential for entropy production). A key question is how this resource could be put to use. To address this issue, it is necessary to consider how the resource is used/wasted at present as well as in a pristine state of nature.

In nature, the negentropy in solar radiation is partly directed by plants into a path of successive transformations in living systems. In each transformation, entropy is produced while the remaining negentropy is keeping plants and animals alive, or even growing. However, of the solar energy directed towards Earth, almost a third is reflected back into space. Of the remaining radiation, some is absorbed in the atmosphere so that only a little less than half reaches the Earth's surface.

Calculating the exact entropy of the different radiation flows involved is difficult. Theoretical contributions have been made by Landsberg (1978), Landsberg and Tonge (1980) and Karlsson (1982). For a quantitative analysis, approximations are necessary and such have been described or attempted by Peixoto et al. (1991), Pelkowski (1994), Weiss (1994), O'Brien and Stephens (1995), Klippel and Müller (1997) and O'Brien (1997). A simple approximation is to assume incoherent blackbody radiation in all stages. Then, the radiation emitted from the Sun is calculated with Stefan-Boltzmann's law, Eq. (1). The fraction of that radiation impinging the Earth's atmosphere is given by

$$\frac{\pi r_j^2}{4\pi R^2}, \tag{4}$$

where r_j is the radius of the Earth (6.4×10^6 m) and R is the average distance between the Earth and the Sun (1.5×10^{11} m). Approximating further, by assuming that the entropy flow is the energy flow divided by the temperature, the flow of entropy impinging on the atmosphere is given by

$$\sigma T_s^3 \left(\frac{r_s}{2R}\right)^2 \pi r_j^2 = 0.03 \ \text{PW/K}, \tag{5}$$

Here, T_s is the effective temperature of the Sun and r_s is the radius of the Sun (6.9×10^8 m). Assuming also that the Earth radiates as a black body for the wavelengths of Earth temperature heat radiation, and assuming the same relation between energy and entropy flow as above, we get the flow of entropy from the Earth as

$$\sigma T_j^3 4\pi r_j^2 = 0.63 \ \text{PW/K}, \tag{6}$$

where T_j is the effective temperature of the Earth, cf. Essex (1984). Note that the temperature of the Earth used in this expression must be compatible with the energy balance requirement for the model. Note also that these assumptions give a Carnot efficiency factor for the Earth, i.e. we have here neglected the (small) corrections included in Eq. (3).

We see that the Earth emits more entropy than it receives. The difference, 0.6 PW/K, corresponds to the rate of entropy production on the Earth.

The rate of commercial energy use of the human society is ≈ 10 TW. If we assume that the energy is converted to heat at Earth temperature, the corresponding entropy production is 0.04 TW/K. The natural rate of entropy production is 15 000 times larger.

Even considering that only about half the solar radiation avoids reflection and absorption in the atmosphere, the natural entropy production at the surface of the planet is ≈ 7500 times the production of entropy by the human society.

Of the potential entropy production only some 5% is delayed as the negentropy is conserved in evaporated water and heat in the atmosphere (Karlsson, 1990, p. 98). Living plants delay $<$ 0.1% of the potential entropy production by photosynthesis, storing the resource in chemical form in plants (Davis, 1990).

The distribution of these flows of energy and entropy are far from homogenous around the planet. The entropy production by human commercial energy use corresponds to the entropy production of some 6×10^4 km^2 average land surface. On the basis of empirical values for solar inflow, we see that an area about five times as large, located in African or North American deserts, is sufficient to substitute global entropy production from commercial sources of energy with solar energy, which would be converted into entropy-free electricity at 10% efficiency. A square (500 × 500 km) of Saharan desert could in this manner substitute all energy used. The part of the Earth required for providing compensation for societal entropy production is thus quite small.

Even the larger area necessary when allowing for further energy transformations producing energy carriers like hydrogen or methanol may be easily found without competing with other land-uses, e.g. Winter et al. (1991). However, it is not likely, or even suggested, that these potentials should ever be used as there are other ways to channel natural entropy production into the industrial system via wind energy, bio-mass wastes, hydropower and different solar heat technologies.

The area calculated for appropriation of solar energy is of the same order of magnitude, 10^5 km^2, as the combined area of hardened roads for cars and of human buildings, or one order of magnitude less that of global urban areas, 10^6 km^2. The area used for agriculture is $\approx 10^7$ km^2, and according to Vitousek et al. (1997), $> 10^8$ km^2 of land area is already manipulated by human activities. The data is from Meyer and Turner (1994).

Thus, human societies have an enormous potential for expanding their procurement of negentropy, without increasing but, if anything, rather lowering the global rate of entropy production. This may be done without interfering more than at present with the natural ecosystems and their conversions of energy and materials. It is even possible to decrease the human appropriation of the products of natural photosynthesis, giving more room for other species.

6. Concluding remarks

Even if there is an enormous theoretical potential of available solar exergy, there must be available technologies to harness this potential. Human societies have relied on indirect forms of solar energy for most of their existence. Furthermore, though the potential is enormous, it is limited. First of all, there is a limit set by the total incoming resources of negentropy. Secondly, there are practical constraints because of competition for areas available for intensive exploitation. Existing technologies for transforming solar energy into energy carriers suitable for transport or further conversion perform with efficiencies in the order of 10%.

The limited stocks of our globe have relevance for the amounts of different chemical elements that we may use. Restrictions to human use of materials are of two kinds. First, there is the resource scarcity limitation that appears as extraction of, e.g. metals, has emptied the ores and the metal has to be extracted from minerals with lower concentrations. Then, the cost of extraction increases both measured in economic terms and in terms of negentropy needed. Second, societal material use tends to produce emissions into the ecosphere of dispersed, high entropy matter as pollution.

However, materials used in society and dissipated in nature do not need to be lost forever. There is no reason why metals, traditionally extracted from mines in concentrations higher than in the average crust, cannot be extracted from soils, bio-mass or seawater. Extraction of cadmium from contaminated soils may be done using *Salix* plantations. Using solar energy, *Salix* trees extract cadmium from the soil. When *Salix* is burned, the cadmium may be extracted using a small fraction of the stored solar energy. The costs of cadmium extracted in this way would presently exceed the world market price of cadmium by much, but it could still be an economically relevant method since the extraction costs may be lower than the estimated environmental costs of cadmium contamination.

Technologies exist that can transform solar radiation into low entropy energy carriers, such as electricity or fuels. In the 1960s, direct conversion of solar radiation into electricity using photovoltaic processes was put to use. But these first attempts were not good enough to make solar cells a plausible technology to supply the exergy needed in industrial society. The reason was that the energy cost of producing the first solar cells was larger than the electricity they delivered while in operation.

While that was true in the beginning, it is no longer the case. There has never been any theoretical, thermodynamic reason why photovoltaic cells should not be produced using less energy than they deliver. Since the 1970s, it has been shown that photovoltaic systems can be made (Herendeen et al., 1979; Mortimer, 1991) and are made (Palz and Zibetta, 1991) in such a way that they are clearly net contributors to an industrial energy system. Both technologies for direct conversion of solar energy via photovoltaic systems and indirect use of solar energy, such as wind power plants, can be built today so that they produce the electricity required for their production in about a year or less (van Engelenburg and Alsema, 1994a,b, Alsema, 1996).

Given a certain area, the amount of resources available for societal productive purposes will depend on the efficiencies of the technologies used in harnessing solar radiation. For some of the available technologies, there may be increases in costs due to restrictions on what may be a sustainable use of materials (Andersson et al., 1998).

We have shown that in physics perspective, solar radiation offers more resources than needed for global industrialisation. Furthermore, technologies are already available for running all currently fossil-fuelled processes with solar energy alone.

In 1970, Georgescu-Roegen wrote “for all practical purposes man has no control over the flow of solar radiation”. And a little later he concludes in a famous passage, “Every time we produce a Cadillac we do it at the cost of decreasing the number of human lives in the future”. The conclusion could follow if the quoted statement of human inability were true, not only at the time it was written, but also forever. But as described here, we do have the ability to control, not the solar output, but the solar radiation used for practical purposes today, and it is possible and desirable that this ability will increase in the future. As a consequence, we may see an industrial society independent of the Earth’s deposits of low entropy resources, a society that, like natural ecosystems, uses the solar radiation to manage and reduce the entropy of matter. The lifetime and total population of such a society would be independent of the number of Cadillacs once built. Thus, that particular conclusion of Georgescu-Roegen is wrong.

In the late 1960s and early 1970s, Georgescu-Roegen’s pessimistic view on the practical possibilities of using solar energy may be understandable. Even then, however, it would have been justified to distinguish between the performance of the technologies of the day and the theoretical limits described by thermodynamics.

Georgescu-Roegen describes how Stanley Jevons in ‘The Coal Question’ laid himself open to criticism because he took the firm position that man will not find another substitute for coal as a source of free energy. Georgescu-Roegen then goes on to say that: “Had Jevons referred to the reserves of low entropy in the Earth’s crust instead of coal ... he would have presented us with a clear picture of one side of man’s struggle with the limited dowry of mankind’s existence on earth” (Georgescu-Roegen, 1971, p. 295–296). Our point is that this limited dowry is not the only source of negentropy for societal use either.

Georgescu-Roegen’s main contribution is in stressing the relevance of the entropy law to describing and identifying limits of the possible economic processes. His major errors concern the description of the long-term resource base and, thus, the possible future development of human society.

Acknowledgements

We thank Professor Robert U. Ayres, Fontainebleau, France, Dr. Katalin Martinás, Budapest, Hungary, Karin M. Granström, Karlstad, Sweden, as well as Professor Karl-Erik Eriksson and Dr. Kristian Lindgren, Göteborg, Sweden, for valuable comments. We accept full responsibility for all remaining deficiencies. The support of the European Commission through the Grant ICOP-DISS-2168-96 to the Carnet-2 network and of the Bank of Sweden Tercentenary Foundation: through grant 90-0144:3 is gratefully acknowledged.

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