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A reexamination of the role of thermodynamics for environmental economics

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Abstract

As the discussion about the role of thermodynamics in environmental economics has not led to a conclusion yet, a more fundamental approach seems to be necessary which also takes into consideration the relationship between economics and the natural sciences in general. To this end value theory is chosen as a starting point because it is the centerpiece of every economic theory. It is shown that neoclassical environmental economics suffers from serious deficiencies because of its value concept heedlessly copied from classical mechanics. Thermodynamics can be expected to be helpful to redress these defects because the economy can be thought of as a dissipative structure dependent on its environment. The obvious way to integrate thermodynamics consists in the formulation of thermodynamic constraints to complement neoclassical environmental economics. But this approach remains unsatisfactory because the neoclassical mechanical hardcore is incompatible with the entropy law and its implications. Evidently, the neoclassical paradigm and its value concept have to be given up. But the alternative of the energy theory of value must be rejected because its determinism cannot be reconciled with the richness of human behaviour. As thermodynamic analogies offer no solution either, there is a dilemma between the necessity and the apparent impossibility of adequately integrating thermodynamic concepts. It turns out that a normative inconsistency is responsible which is due to the demand for intergenerational justice. Therefore, the integration of thermodynamics into environmental economics hinges on a meta-economic value decision. If sustainability is adopted as the guiding principle, the insights of thermodynamics call for a macro-economic environmental policy setting absolute limits to the economy. But this macro policy is incompatible with neoclassical economics so that a social reconstruction of economics, based on a social theory of value, becomes necessary. In sum, thermodynamics is important for environmental economics: besides fulfilling a general heuristic function, it also fulfils a decisive conceptual and an analytical function insofar as it helps to justify sustainability and to operationalize macro-economic environmental policy. © 1997 Elsevier Science B.V.

Keywords: Thermodynamics; Environmental economics; Meta-economic value decision

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1. More heat than light

The role of thermodynamics for economics in general and for environmental economics in particular has been intensely, and sometimes passionately, discussed since Georgescu-Roegen (1971) published his seminal 'The Entropy Law and the Economic Process'.[2] It is not surprising that ecological economists with their specifically interdisciplinary approach have paid much attention to thermodynamic concepts; but even among them opinions range from enthusiastic acceptance to hostile dismissal, and a consensus has yet to emerge. Unfortunately, this confusion provides some justification for the attitude of most neoclassical environmental economists towards thermodynamics: it is deemed irrelevant and consequently either ignored or, sometimes, explicitly rejected.

A broader and more comprehensive approach is necessary to bring some light to the heat of the discussion—an approach which must not be narrowly confined to the instrumental use of thermodynamic concepts, but also must take into consideration the relation between economics and the natural sciences in general. To analyze this relation, value theory is suggested as the point to start: it is the centerpiece of every economic theory and shows the pervasive influence of the natural sciences most clearly (Section 2). Section 3 briefly describes the physical origin of neoclassical economics and the resulting shortcomings of neoclassical environmental economics. The necessity and the possibilities to alleviate these shortcomings through the integration of thermodynamic concepts are discussed in Section 4. After answering the question of *whether* to integrate thermodynamic concepts in the affirmative, we turn to the question of *how* to integrate them. All approaches, however, turn out to be insufficient—albeit for different reasons. In Section 5 we try to resolve this dilemma and draw some consequences for the development of environmental economics, but also for economics in general. What we will not do is to provide a summary of thermodynamics because even sketching only its barest essentials would go beyond the scope of an article. Instead the reader is referred to textbooks such as Adam and Hittmaier (1988) or Callen (1985) and to the Encyclopaedia Britannica article of Keenan et al. (1989).

2. Value theory and natural economics

These days value theory is generally considered to be nothing more than metaphysical speculation and therefore completely irrelevant to 'real' economics—just a remainder of the pre-neoclassical period of missing scientific rigour in economics, or political economy as it was then called. But this relegation of value theory to the margins of economics could not be less justified. Contrary to mainstream opinion, value is of decisive importance for every economic theory because of its epistemological role as a conservation principle (Heilbroner, 1983).

Conservation principles are the fundamental heuristic devices common to all fields of science (e.g. in physics, the conservation of energy is of utmost importance). It is they that make the formulation of theories and the postulation of laws possible because causalities can only be identified if everything is not variable, if there is some constant and invariable entity against whose background causal relations can be observed (Meyerson, 1930, 584ff). Conservation principles are assumptions, assumptions that may be plausible and useful but that are not strictly true and that cannot be proved because in reality nothing at all is invariant and unalterable. In economics the conserved entity is called value.

> Value in the economic sphere may be regarded as the imposition of a set of invariance principles which are factually false but are eminently

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[2] For recent contributions to this debate, see Bianciardi et al. (1993), Binswanger (1993), Khalil (1990, 1991), Lozada (1991), O'Connor (1991) and Williamson (1993) in *Ecological Economics*; Daly (1992b), Townsend (1992), and Young (1991, 1994) in the *Journal of Environmental Resources and Management*; Burness and Cummings (1986), Burness et al. (1980) and Daly (1986) in *Land Economics*. For precursors of Georgescu-Roegen, see Georgescu-Roegen (1986b), Martinez-Alier (1987) and Proops (1985).

> useful on both a pragmatic and a deeper conceptual level. (Mirowski, 1990, 695)

Value theory is the centerpiece and the foundation of economics; it not only has to establish the economic conservation principle, but also must provide a justification for it because this principle must not, despite its axiomatic character, be chosen totally arbitrarily: different principles may be more or less suited to building explanations of economic phenomena upon. In this context, the distinction between the theoretical and the practical conservation principle is important: economists as scientists are in need of the former whereas the objects of their research, economic men, depend upon the latter to make plans and to make sense of their actions and those of others. Both principles need not be identical. The importance of value theory notwithstanding, not every economist needs to be aware of the value concept he is using; it is possible to have a value concept without a value theory.

Which conservation principles have actually been used in economic theory? Quite surprisingly, all important economic conceptions were based on 'natural' conservation principles, conservation principles, that is, which were derived from the natural sciences, especially physics. On the one hand, there are the substance theories of value, inspired by Cartesian physics, which locate value in some substance, i.e. within the goods; the Physiocrats (corn), Adam Smith (stock) and Marx and Ricardo (labour) belong to that category. On the other hand, there is the field theory of value which is at the heart of neoclassical economics: value—modelled according to the energy field of classical mechanics—is equated with utility and thus no longer resides in the goods but in the individuals' minds, i.e. their preferences.

The physical origin of these conservation principles is but one episode, albeit an important one, in the long history of exchange between the natural and the social sciences which served to reconcile the need for conservation principles with the demands of positivism, the epistemological doctrine dominant until the first half of the 20th century. Their heuristic and axiomatic character being unacceptable to positivism, conservation principles somehow had to be grounded in 'facts'—or at least it had to look that way. Therefore, natural and social conservation principles were not postulated independently, but were transferred from the social to the natural realm and vice versa so that they could justify each other—although neither was really 'true' (Mirowski, 1989, ch. 3).

> The social body constrains the way the physical body is perceived. The physical experience of the body, always modified by the social categories through which it is known, sustains a particular view of society. There is a continual exchange of meanings between the two kinds of bodily experience so that each reinforces the categories of the other. (Douglas, 1982, 65)

This bilateral exchange became heavily biased towards the transfer from the natural to the social sciences when, due to the achievements of classical mechanics, physics rose to the top of science. Consequently, economists increasingly looked for physical concepts to guide their research and provide them with conservation principles—a development which culminated in the construction of neoclassical economics (Section 3). But since then things have changed—the insight that truth is not just discovered, but also partly 'constructed' by our scientific activities, has made positivism more and more obsolete so that conservation principles can now be accepted as what they are and do not any longer have to be tied to some purported 'objective' foundation. Rather they can be chosen according to the needs of the respective discipline from whose point of view only their adequacy is to be judged.

Therefore, the justification for economic conservation principles needs to be economic. Of course, this does not exclude the transfer of concepts from the natural sciences to economics, as long as there are good economic reasons for it. The economic justification generally will become increasingly difficult (and increasingly important!) as the transfer becomes more intense. Basically, there are three levels of intensity: firstly, there is interdisciplinary cooperation, the 'mildest' form of transfer; in this case, economically relevant results of the natural sciences are incorporated into the protective belt of the respective economic theory by way of additional constraints so that its hard core will not be affected. Next, the hard core itself may be derived from the natural sphere through analogical or, less important, metaphorical reasoning. [Although there is no clear-cut dividing line, one may say that analogies are more structured and more exact and serve as a means of explanation, whereas metaphors tend to be used only illustratively, more loosely and without an immediate explanatory purpose.] Finally, an independent economic hard core may even cease to exist, if economics is completely explained in natural terms, i.e. is reduced to the status of a subdiscipline of, e.g. physics. In Section 4 we will encounter all three kinds of transfers.

3. Neoclassical environmental economics: its origin and its shortcomings

The prime example of physics envy and the desire to emulate the natural sciences is, of course, neoclassical economics which was explicitly and purposefully copied from classical mechanics.[3]

At the center of the hard core of neoclassical economics is the analogy between (potential) energy and utility.

> The key to understand neoclassical economics is to realize that prices constitute a conservative vector field (…) such that, given a scalar field of utility (…), the price vector may be deduced from it. (Mirowski, 1989, 223)

Not only was the value concept, utility, derived from classical mechanics—the same goes for the behavioural assumption, maximization of utility.

Although the neoclassical pioneers followed the analogy very closely, there were a few notable deviations: firstly, the ‘law’ of one price was postulated, which facilitates the solution of optimization problems, but which is hard to justify economically. Secondly, and more importantly, the conservation principle, which states the constancy of the sum of expenses and utility, and the corresponding integrability conditions, which imply equal elasticities of substitution in equilibrium, were discarded—partly because of their economic absurdity, but above all because the ontological identity of money and utility would have jeopardized the neoclassical project of a ‘scientific’ economics independent of social institutions. As every field formalism depends on some conservation principle, however, a substitute had to be adopted, one that would allow for income effects. It was found in the guise of the infamous Slutsky integrability conditions (i.e. the negative semi-definiteness and symmetry of the Slutsky matrix); they correspond to the constancy of the sum of expenses and *constant* utility.

For neoclassicism to become a complete economic theory, the mechanical analogy had to be applied to production, too. Here (potential) energy is equivalent to output that is maximized for given costs. Implying the constancy of the sum of costs and output and thus being hard to interpret economically, the original conservation principle was replaced by various substitutes (such as the assumption of constant returns to scale) which look innocuous, but actually do not differ materially. The mechanical analogy involves symmetrical technology, reversible and instantaneous production and, in principle, unrestricted factor substitutability so that it is even more implausible in the production than in the consumption case.

What consequences does this mechanical origin have? On the one hand, neoclassicism must be as deterministic, reversible and atemporal as its physical counterpart. On the other hand, the only important economic modification—the substitution of the Slutsky integrability conditions for the mechanical conservation principle—led to additional difficulties: firstly, some highly esteemed qualities of mechanics were lost; in neoclassical economics at most the existence of an equilibrium can be guaranteed, not its uniqueness or stability. Secondly, the Slutsky conditions were treated as a mere technicality of no ‘real’ economic importance. In particular, the conservation principle corresponding to the Slutsky conditions was never

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[3] As this issue has been discussed extensively elsewhere (de Marchi, 1993; Mirowski, 1989), there is no need to go into details.

spelled out because it would have revealed that money and utility still are basically identical. That is why neoclassicism has a *value concept*, mechanical utility, but is lacking a *value theory*. Thus, a critical discussion of the basic conservation principle at the heart of neoclassical economics, of its mechanical value concept, never could take place, although it is responsible for most of its problems—not the least of which is its conception of nature.

The economy is essentially regarded as clockwork, isolated from and independent of its environment (Georgescu-Roegen, 1976, 4; Georgescu-Roegen, 1981, 44f). Insofar as the existence and importance of the environment is acknowledged, it is not seen as a limiting factor for economic development because infinite supplies of both natural resources and waste absorption capacities are implicitly assumed (Daly, 1987, 323; Perrings, 1987, 4ff). So deeply ingrained was this attitude that Boulding's (1968) rather trivial concept of the 'spaceship earth' was enthusiastically celebrated as 'one of the most enlightening ideas' (d'Arge, 1972, 11). This 'enlightenment', together with environmental problems becoming more and more acute, contributed to the establishment of neoclassical environmental economics. [Of course, there were neoclassical precursors who discussed environmental issues, but before the new subdiscipline came into being in the 1960s, the environment was not systematically integrated into economic analysis.] It is based on the neoclassical hard core whose positive assumptions, derived from the central mechanical value concept, include methodological individualism, individual rationality, substitutability and the allocative efficiency of ideal markets. Welfare economics provides normative complements: the objectives of either Pareto optimality or the maximum of a (in most cases utilitarian) social welfare function. This analytical apparatus is applied to the environment and its economic functions—supplier of natural resources and absorber of wastes. They are, in general, separately examined so that neoclassical environmental economics can be subdivided into resource and externality economics. As the standard results are well-known, suffice it to sketch only their essence. Basically, the allocation of environmental goods ought to be left to the market as far as possible. This is regularly the case with natural resources because sufficiently well-defined property rights exist or can be easily created. Intergenerational justice and the possibility of a rapid exhaustion of natural resource deposits are reconciliated by invoking substitution possibilities and technological progress, which are believed to prevent any resource-related problems for future generations.[4] In contrast, externalities (or, at least, most of them) require some intervention by the state—ideally in the form of Pigou taxes. Although there may be some practical problems (which led to a watered-down approach substituting cost minimization for Pareto optimality), these interventions are, in principle, able to realize Pareto optimality and thus to solve the pollution problems.

However, neoclassical environmental economics is far from having really solved, even theoretically, all the problems relating to the interactions between economy and environment. Like all of neoclassical economics, it bears the hallmark of mechanics and is thus also haunted by the conceptual a-naturalism so typical of neoclassicism, which is responsible for some very grave deficiencies of standard neoclassical environmental economics.[5]

Firstly, natural limits to growth are ignored. Of course, the finiteness of the earth and its resources and absorptive capacities is not denied; but it is deemed irrelevant: thanks to substitution possibil-

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[4] Although not explicitly incorporated into the normative part of the neoclassical hard core, the need to care for posterity is, at least implicitly, acknowledged by most neoclassicals. With very few exceptions, such as Burness and Cummings (1986), they do not dismiss intergenerational justice as irrelevant or unimportant.

[5] In what follows only those shortcomings will be mentioned which can possibly be alleviated through a recourse to thermodynamics. For a broader critique, including also social and political aspects, see, e.g., Bromley (1991) or Söllner (1993). Furthermore, our critique applies only to standard neoclassical environmental economics, not to those approaches that try to take thermodynamic concepts into account. Because of these extensions of the neoclassical paradigm, there is not really a clear-cut dividing line between neoclassical environmental economics and ecological economics.

ities and technical progress, there are only physical limits, but no economic limits. This position is put forward most enthusiastically by Simon: "[T]here is no meaningful physical limit—even the commonly mentioned weight of the earth—to our capacity to keep growing forever." (Simon, 1981, 346) This optimism is not grounded in facts but, on the contrary, on the disregard for important natural laws. For one thing, resources are heterogenous and though some or even many may be substituted for, it is by no means possible to find substitutes for all of them:

> We cannot, to give a crude example, envisage the substitution of lead, uranium, or mercury for wheat, rice, or cassava as a staple in the human diet. The heterogeneity of resources under less than perfectly flexible production and consumption technology means that the exhaustion of resources is not only possible, but may be economically significant. (Perrings, 1987, 126)

In any case, it is not possible to deduce from the substitutability of resources the irrelevance of the finiteness of natural resources in general. After all, there is no matter except natural resources: ex nihilo nihil fit! The arguments in favour of unending technological progress do not stand close scrutiny either (Aage, 1984); even theoretically, technological progress cannot be unlimited. Above all, the laws of thermodynamics indicate minimum energy requirements for every process.

> To be sure, actual efficiency depends at any one time on the state of the arts. But, as we know from Carnot, in each particular situation there is a theoretical limit independent of the state of the arts, which can never be attained in actuality. In effect, we generally remain far below it. (Georgescu-Roegen, 1976, 11).

And, of course, a really inexhaustible source of energy—the 'backstop technology' that figures so prominently in neoclassical resource economics—is physically impossible. Because of these restrictions, the problem of intergenerational justice cannot simply be 'solved' by referring to substitution and progress; rather it has to be accepted as a real problem that merits serious discussion.

Secondly, important interdependencies are neglected. On the one hand, the separation of resource and externality economics tends to conceal an otherwise obvious relation: all material inputs sooner or later end up as waste—either as pollution during production or consumption or, insofar as there is no recycling, as garbage; "waste is an output just as unavoidable as the input of natural resources" (Georgescu-Roegen, 1976, 13). On the other hand, within each subdiscipline oversimplification reigns: although mineral resources can be dealt with separately, the same approach is clearly not feasible for renewable resources where highly complex ecological interrelations exist. For example, the economic exploitation of a certain species is bound to have considerable effects on other species in the respective food chain. Similar problems abound in the case of pollution: pollutants cannot be eliminated, but only be transformed into a less inimical form so that, for example, a reduction of the SO_2 emissions of power plants can only be achieved at the cost of additional solid waste (sledge from wet scrubbing). The usual partial analytical approach focusing only on one pollutant at a time is therefore clearly inadequate. Furthermore, pollutants interact with one another in a variety of ways; often it is not even in principle possible to determine the social cost of a single pollutant and charge the polluter with the efficient Pigou tax—to say nothing of practical problems and our imperfect knowledge of these interactions. Therefore, the externality problem cannot be expected to be solved just by "simple and knowable things" (Solow, 1973, 50). Contrary to neoclassical assumptions, there is no complete controllability of the environment because of these pervasive interdependencies (Perrings, 1987, 49f).

Thirdly, the important role of time is not recognized. Often even its very existence is denied when producers, consumers and regulatory agencies are assumed to act or react immediately. Even if time is taken into account, it is treated, not surprisingly, in a mechanical fashion: genuine uncertainty does not exist, there are no real surprises;

everything is known—either with absolute cer tainty or at least in the form of some probability distribution (Edmonds and Reilly, 1985; Georgescu-Roegen, 1971, ch. 5–8; Perrings, 1987, ch. 8). Moreover, reversibility is assumed; the economy-environment interactions proceed in infinitesimal, qualitatively identical and reversible steps; there are no critical thresholds, no points of no return. No matter what will be done to nature, it can be undone: "We can replant forests, de-pollute water, rebuild our city centers, and re-landscape our suburbs and the scenery around our highways." (Johnson, 1990, 24) From this point of view potentially catastrophic developments (such as the greenhouse effect) cannot be appreciated. Even the introduction of the concepts of option value and quasi-option value is no effective remedy as they treat irreversibilities as rare exceptions to the rule whereas, of course, all real economic (and other) processes are irreversible.

The three critical points must not be seen as isolated from one another. For example, technological optimism makes it easier to assume reversibility, which in turn may justify the negligence of complex interactions. The intimate interrelation of these issues—which is most obvious in the case of the neoclassical production function—is due to their common cause, the mechanical hard core of neoclassicism. Still, neoclassical environmental economics provides important insights into the character of environmental problems, and it definitely makes sense to apply neoclassical concepts to many of these problems. But because of its unmistakable shortcomings, neoclassical environmental economics is clearly unable to cope with *all* environmental problems, especially if serious or long-term consequences are involved. Therefore, an integration of thermodynamic concepts seems to be necessary for a more 'natural' environmental economics. Indeed, limitlessness and atemporality directly result from the mechanical, that is, non-thermodynamical, character of neoclassicism, whereas oversimplification is not primarily a consequence of mechanics per se, but rather of the restriction to a mechanics of conservative and isolated systems.

4. The integration of thermodynamics into environmental economics

The main part of this paper will deal with the various possibilities to integrate thermodynamic concepts into environmental economics.

On the one hand, additional thermodynamic constraints may be added to neoclassical environmental economics, derived either from classical or from statistical thermodynamics (Section 4.2). On the other hand, the neoclassical value concept may be replaced by an energy theory of value (Section 4.3). Furthermore, although they are not directly relevant to environmental economics, we will have to mention thermodynamic analogies (Section 4.4). The results of our discussion will be briefly summarized in Section 4.5. But first of all the relevance of thermodynamic concepts for environmental economics has to be shown (Section 4.1).

4.1. Is it relevant?

Of course, it is! To see why, let us have a closer look at the interactions between economy and nature.

The earth is a closed system which exchanges energy, but not matter with its environment. The economic system is located within the closed system earth. Its elements are men, insofar as they make economic decisions, and the goods and the money they hold; economic men are related to one another by flows of money and goods. Of decisive importance is the fact that only the money flows (not drawn in Fig. 1) constitute a closed circle within the economic system. The goods, in contrast, do not circulate: they are produced with the help of natural resources which have to be 'imported' from the environment. Their production or their consumption may cause waste and they themselves—unless they are immaterial goods (services) or unless they are recycled—inevitably end up as waste; all that waste has to be 'exported' to the environment (except for the garbage that is deposited in an orderly way). As the earth is finite these interactions are by no means negligible: the 'imports' deplete the resource stocks and the 'exports' may have detri-

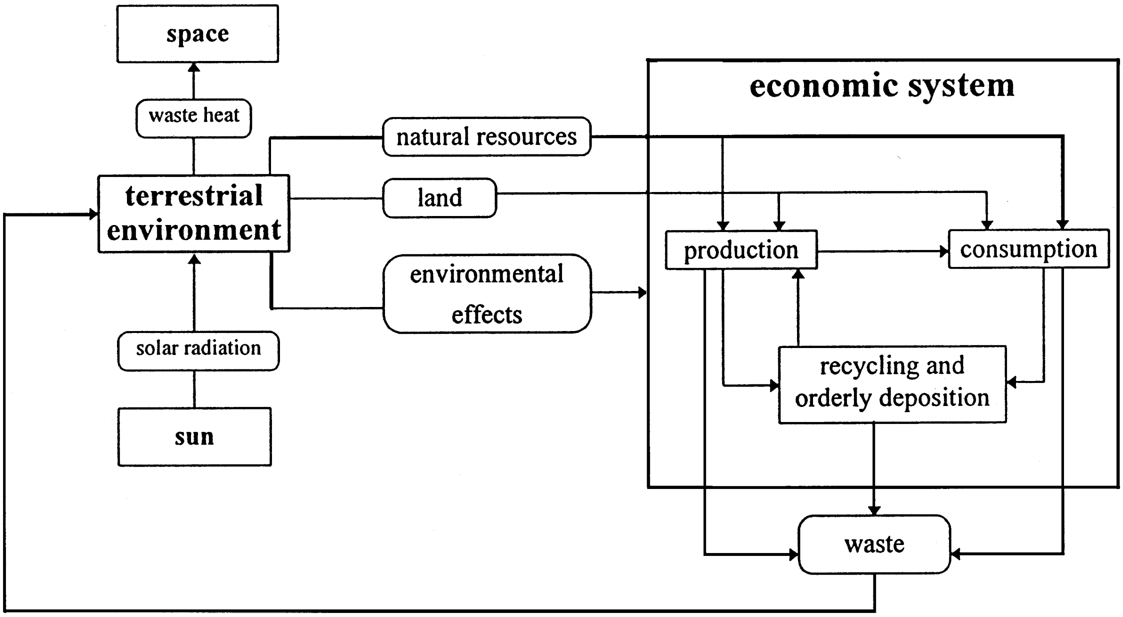

Fig. 1. The relations between economy and environment.

mental effects on the economic system and on human society in general. The services of nature come from outside the economic system; there are no money flows to and from nature. Natural resources (and land) are assigned economic values within the economy, but their transfer itself from nature to economy is not an economic, but a legal act, an appropriation carried out through the creation of property rights. Environmental effects are, due to the absence of well-defined property rights, not economically valued (which is why their arrow in Fig. 1 does not cross the border of the economic system). The policy prescriptions of neoclassical externality economics aim at bringing about this valuation (by means of Pigou taxes, for example), but even if all of these effects were correctly valued, environmental goods would still be appropriated, albeit in a 'regulated' manner. Nature is not economically controllable (Perrings, 1987, 82); in this sense there will always be 'external effects'. The economy must be an open system exchanging matter and energy, a system dependent on its environment.

And how can thermodynamics contribute to the understanding of this relationship? The relevance of the first law of thermodynamics, the law of the conservation of energy, is conceded by all economists, above all, because it also implies (due to Einstein's matter-energy equivalence) the conservation of matter, which is the obvious reason for scarcity and thus for the need to economize: "man cannot create material things." (Marshall, 1959, 53)

In contrast, the economic relevance of the second law of thermodynamics, the entropy law, is very controversial. [For this discussion, see the literature quoted in footnote 2.] On close inspection, however, it becomes clear that the second law is as important as the first: as we just pointed out, the economy is an open system. Since each and every economic process requires energy, which—when used under less than ideal conditions—becomes irreversibly downgraded, the economy may maintain or develop its structure only by the dissipation of energy, that is, by the production of entropy. Therefore, it is not in thermodynamic equilibrium; it is not even in a steady state because entropy production is not constantly minimal. From the point of view of thermodynamics the economic system is to be interpreted as a dissipative structure[6]; "the economic process is entropic: it neither creates nor consumes matter or energy, but only transforms low into high entropy." (Georgescu-Roegen, 1971, 281) The economic importance of entropy production derives from the finiteness of the stocks of available, that is, useful energy (exergy) and the irreversibility of the depreciation of energy; once used energy will become less available, its quality will decrease; eventually it will end up as waste heat—completely useless. That is why "the Entropy Law is the taproot of economic scarcity." (Georgescu-Roegen, 1976, 9)

The economic relevance of the entropy law can be seen more clearly if three different time horizons are distinguished (Daly, 1987, 325). In the long run, the very long run, the ultimate frontier for all of human life, and thus all economic activities on earth consists in the death of our sun, which is fortunately still billions of years away; until then we will be provided with a constant, but finite, stream of low entropy (in the form of solar radiation) to (over-) compensate the entropy production on earth. More important is the medium run when we will have to confront the exhaustion of fossil fuels. The switch to solar energy (or nuclear power), which is in principle possible, constitutes a major economic problem because our present economic structure is adapted to and relies heavily upon the massive use of hydrocarbons as energy sources. (Ayres, 1988, 288, 294f; Ayres, 1991, 258; Georgescu-Roegen, 1982, 32; Georgescu-Roegen, 1986a, 234ff; Hall et al., 1986, 8, 103f; Hubbert, 1993; Slesser, 1993; Wicken, 1986, 268.) Severe economic disruptions will occur, if the inevitable structural change comes as a shock—which is all too likely, if the implications of the entropy law are not paid attention to. Finally, in the short run, the entropy law may serve to draw attention to the possibility of catastrophic, irreversible developments, the complexity of ecological systems and their interactions with the economy—by way of the 'arrow of time' and the concepts of non-linear thermodynamics.

However, not too much must be read into the entropy concept and the law of its increase. Changes of entropy are important, not absolute amounts. The entropy production of economic processes is decisive, not the entropy content of the economy. There is no immediate connection between entropy content and complexity or degree of organization of an economic system. Thermodynamics may reveal the necessary conditions for the existence and development of the economic system, but it cannot fully explain it, let alone forecast its future (Proops, 1983, 361; Georgescu-Roegen, 1971, 282f). By the same token it is not possible to speak of low entropy as a necessary attribute of economic (i.e. valuable) goods, as Georgescu-Roegen (1971, 278) does; entropy being an extensive quantity, there is no clear-cut dividing line: a car has a much higher entropy than some weed whose entropy in turn may exceed that of a truffle.

Nonetheless, the entropy law can hardly be denied its relevance for environmental economics. In fact, it is only the combination of the first and the second law of thermodynamics that causes the economic problem (Daly, 1992b, 94): without the first law the second would be irrelevant as we could create energy anew. With the second law invalid, energy could be used over and over again and the resulting energetic affluence would take the bite out of the first law, above all by making complete recycling less unrealistic.

4.2. Thermodynamic constraints

The most obvious method to deal with the deficiencies of neoclassical environmental economics consists in the formulation of additional thermodynamic constraints, which can be based upon classical or statistical thermodynamics.

4.2.1. Classical thermodynamics

The 'classical' thermodynamic constraints can be derived from the materials balance approach

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[6] Ayres (1988, 288ff); Ayres (1991, 261); Ayres and Kneese (1989, 106f); Binswanger (1992, 21f); Binswanger (1993, 213); Bruggink (1985, 141f); Proops (1983), (1985, 67ff); Wicken (1986). Of course, the economy is primarily a social system. It has to be emphasized that we regard the economy as a dissipative structure only insofar as the interactions with its environment are concerned; we do not intend to propagate thermodynamic reductionism.

or from energy analysis, which can also be applied in combination. Besides, Georgescu-Roegen suggests a 'fourth law of thermodynamics', which he believes to provide additional important constraints.

4.2.1.1. Materials balance approach. The materials balance approach as such was introduced by Ayres and Kneese (1969) and Kneese et al. (1970), although its central idea was already put forward by Boulding (1968) and Daly (1968). It is based on the first law of thermodynamics, specifically on its implications for matter: as in a closed system (such as the earth) matter is (approximately) conserved, the sum total of the earth's matter is constant. [Minimal losses (which may be due to nuclear fission and fusion) and gains (from meteorite impacts, for example) can safely be neglected].

From this obvious fact important constraints concerning the relation between the economy and its environment can be deduced. For the economy as a whole, within a certain period the mass of natural resource inputs must equal the sum of the masses of waste and accumulation (in the form of durable consumer goods or capital); if there is recycling, an increase (decrease) of the mass of recycled matter is to be added to (deducted from) this sum. Equivalently for single economic units, within a certain period the mass of material inputs (either from nature or from other economic units) has to be equal to the sum of the masses of material outputs (either to nature or to other economic units) and accumulation; in the case of recycling the above modification applies analogously.

These, and similar, constraints may be integrated into macro- or micro-economic models where they lead to important insights: on the macro-economic level the finiteness of the earth's resources and absorptive capacity as well as the intimate relation between resource input and waste output can be taken into account explicitly. It becomes clear that "[t]echnological external diseconomies are not freakish anomalies in the processes of production and consumption, but inherent and normal parts of them" (Kneese et al., 1970, 14). Furthermore, by emphasizing the fact that pollutants cannot be eliminated, the materials balance approach reveals the complexity of the externality problem and the insufficiency of partial, one-pollutant approaches. On the micro-economic level it becomes obvious that the neoclassical production functions are grossly inadequate: the usual capital-labour functions completely disregard the input of materials and the output of waste, and even if materials are included, unrealistic substitution possibilities are assumed whereas in reality, for example, materials embodied in goods cannot be substituted for by labour or capital.

Therefore, the materials balance approach makes possible a more realistic analysis of economy-environment interactions. However, there is still much left to criticize: firstly, from the point of view of the materials balance approach there are no real limits to growth either. Thanks to the possibility of complete recycling, which cannot be excluded on thermodynamic grounds, there is no real danger of ever running out of natural resources. Even if current recycling is less than perfect, the resources used up are not wasted for good; they are still somewhere out there and can, in principle, be retrieved and reused when the deposits are depleted. Therefore, intergenerational equity is not really a problem. This reasoning, however, only goes for non-energy resources. But, due to its disregard of the entropy law, the materials balance approach also treats energy resources in that way, at least implicitly; their irreversible quality losses, which rule out recycling, are ignored—and thus the problem of fossil fuels and their exhaustion, too. Secondly, the importance of time is still not taken into account. Thirdly, the complexity of the interdependencies between economy and nature is not reflected by the materials balance approach. Not the exclusive focus on the first law of thermodynamics, but the inability of the neoclassical paradigm to incorporate all implications of the first law is responsible for that defect. A paradigm built according to an isolated and conservative mechanical system must assume complete controllability; therefore, it is no surprise that "the most important implication has been almost completely neglected. It is the necessity for any system generating residuals in the process of production to change over time, to evolve from one state to the next as the residuals generated in production are returned to the system in either a controlled or uncontrolled way." (Perrings, 1987, 8)

That is why even neoclassical production functions amended according to the insights of the materials balance approach fail to take into account all relevant physical aspects (Binswanger, 1992, 216ff; van Gool, 1985).

All in all, the materials balance approach can only be the first step towards a more 'natural' environmental economics.

4.2.1.2. Energy analysis. When the oil shocks of the early 1970s drew attention to the vital importance of energy for the economy, a discipline dealing exclusively with energy and its role in the economy began to flourish: energy analysis.

> The aim of energy analysis is to quantify the energy flows inherent in all systems. As applied to economic systems, it is concerned with the energy flows inherent in the production of goods and services. (Gilliland, 1978a, 1)

Energy analysis is motivated by the second rather than the first law of thermodynamics because it is the former which makes energy the 'ultimate resource':

> When all input requirements are analyzed, it becomes clear that energy limits the ability to obtain any input. This had led to the concept of energy as the ultimate limiting factor, which is to say: (i) that energy is the only commodity for which a substitute cannot be found, (ii) that potential energy is required to run every type of system, and (iii) that energy cannot be recycled without violating the second law of thermodynamics. (Gilliland, 1975, 1052).

Although some energy analysts have postulated an energy theory of value (Section 4.3), energy analysis in principle is a positive analysis; and insofar as policy prescriptions are put forward they are based on the conventional, utility-centered economic reasoning.[7] Energy analysis may be divided into three subdisciplines: energy accounting, macro-economic energy analysis and thermodynamic analysis. [Some energy-analytic approaches do not fit in any single category (e.g. Slesser, 1985, 1987).]

Energy accounting is concerned with the calculation of energy costs (both direct and indirect) of goods and services; these energy costs are to be used in analyses, for example, of the effects of energy price changes or different energy policies on the economy. Both variants of energy accounting (gross and net energy accounting) are based on the principle of the conservation of 'embodied energy' according to which the energy costs of all inputs are equal to the energy costs of all outputs of a production process or a firm (Bullard and Herendeen, 1977, 71; Chapman, 1974, 94). Energy accounting suffers from some very intricate technical problems (Bullard et al., 1978; Chapman, 1974; Hall et al., 1986, ch. 5), among which one stands out: due to the lack of physical data, economic input–output statistics have to be relied upon for the determination of energy costs. Because thus the energy costs are calculated in accordance with the prices, constant energy intensities (i.e. constant energy-price ratios across the range of goods) necessarily have to result—a methodological artefact that renders energy accounting almost useless; only the total macro-economic energy intensity matters because, e.g., any energy price change would be structurally neutral.

Macro-economic energy analysis is able to provide more useful information. It analyzes the macro-economic importance of energy inputs, especially in relation to other factors of production. There are two approaches, a qualitative, historical one (Schurr, 1984; Thoresen, 1981, 1985) and, more importantly, a quantitative, statistical one. The latter employs various macroeconomic production functions to estimate elasticities of substitution and production for energy. [Berndt and Wood (1979), Chang (1994), Hogan and Weyant (1982), Kümmel (1980, 1986, 1989).] In general,

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[7] For a discussion about the aims and the scope of energy analysis see Chapman (1977), Common (1976, 1977) and Webb and Pearce (1975, 1977).

the elasticity of production is found to be quite low, which underlines the important role of energy; at the same time secular increases of this quantity indicate improvements of energy efficiency due to technological progress (Hall et al., 1986, ch. 4). The relation between capital and energy seems to be complimentary in the short, but substitutional in the long run.[8] These results allow short-term or, at most, medium-term forecasts of energy demand and are thus of some value for economic policy, especially energy policy. However, macro-economic analysis cannot provide 'real' thermodynamic constraints, but only regularities contingent upon economic structure, technology, etc. The same goes for energy accounting, too, whose results are of little use anyway.

In fact, it is only thermodynamic analysis that establishes 'hard' thermodynamic constraints and on which many energy analysts have focused their efforts (Bruggink, 1985, 137f). Thermodynamic analysis relies mainly on physical and engineering, less on economic, concepts and methods. It calculates the thermodynamic limits, i.e. the theoretical minimum energy requirements, for various processes and compares them to actual energy consumption. Thus the potential for energy savings is revealed—but also insurpassable limits to technological progress.

First-law and second-law analysis may be distinguished: the former takes only the quantity of energy into account. Technical processes are evaluated according to the concept of first-law efficiency—the relation between energy input and energy output which reaches 1 only for ideal, frictionless processes (Ayres, 1978, 43f; Slesser, 1978, 106). The latter considers both the quantity *and* the quality of energy by focusing not on energy per se, but on available energy (exergy). Consequently, the concept of second-law efficiency relates exergy output with exergy input; it reaches 1 only in the case of reversible, infinitely slow processes (Ayres, 1978, 52f; Gaggioli, 1983, 11f). Theoretically, second-law analysis is superior as it is exergy that makes all processes run and it is exergy that really gets used up. "Energy is not the commodity we value; potential energy (availability) is." (Gaggioli, 1980, 12) But in practice, first-law analysis dominates because second-law efficiencies are quite difficult to calculate and because they differ markedly from the results of first-law analysis only in a few cases, e.g. the heating of buildings and water to temperatures below 100°C (Edgerton, 1982, 315; van Gool, 1980b, 786). [For details of second-law analysis, see Edgerton (1982), Moran (1982, 1990).]

The thermodynamic limits may be incorporated into the neoclassical model as additional constraints. They make it unmistakably clear that energy is absolutely indispensable and that, given finite energy resources, the problem of an adequate energy supply is an issue of utmost importance for economics, which cannot be dealt with by some laconic references to substitution possibilities and technical progress. Moreover, thermodynamic analysis is able to show that capital and energy are substitutes before the thermodynamic limits are reached (van Gool, 1980a, 430f; van Gool, 1980b, 790; Phung and van Gool, 1982, 5ff). This is consistent with the findings of macroeconomic energy analysis because only in the long run can energy-saving technologies be implemented on a scale large enough to affect macroeconomic quantities. Due to the substitutional relation between capital and energy, the thermodynamic limits will never be realized in practice. Assuming cost minimization, the thermodynamic optimum will only be realized if the price of capital is zero. Otherwise, economic optimization will generally lead to a higher energy input and a lower capital input (Berndt, 1978, 232ff; Berry et al., 1978).

> Because the cost of work includes not only fuel costs but also capital costs that usually increase as irreversibility in the process is reduced, the economical means of producing work may in some respects depart radically from the reversible means. (Keenan et al., 1989, 618).

The fact that real processes are run in a thermodynamically suboptimal way has consequences

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[8] For the problematic interpretation of the elasticities of substitution, see Atkinson and Manning (1995).

not only for the problem of energy supply but also for the pollution problem. As emission abatement facilities produce waste heat, i.e. are thermodynamically inefficient, too, economic growth will eventually run into the 'heat barrier' even if pollutants as such are somehow made harmless.

> Technological abatement of chemical and radioactive pollution will usually lead to enhanced thermal pollution as a consequence of the Second Law of Thermodynamics. (Kümmel, 1986, 1020)

However, there is an interesting parallel between thermodynamic analysis and the materials balance approach; both are necessarily based on ideal cases—the latter on perfect recycling and the former on reversibility. The thermodynamic limits refer to ideal, reversible processes which do not dissipate energy. Consequently, if they were realized, neither the finiteness of energy resources nor the possibility of a heat barrier would matter. Of course, economic optimization will entail higher energy inputs and considerable entropy production so that in reality there will be energy-related limits to growth. But the neoclassical paradigm cannot adequately allow for these limits because reversible processes must be assumed as alternatives whose non-realization due to economic reasons has to be accepted as efficient and Pareto-optimal. However, there is one crucial difference to the materials balance approach: whereas wasted matter can still be recycled, should need be, available energy, once wasted, is gone forever and cannot be recycled. Therefore, in the case of energy the usual neoclassical results cannot be easily reconciled with intergenerational justice; 'backstop technologies' have to be resorted to: "unfortunately (…) 'substitution forever' and 'infinite technological progress' (…) do not hold for energy resources: they have to violate thermodynamic laws. (…) Thermodynamic laws enforce the use of some back-stop energy in the future" (Ströbele, 1985, 75). But it is these thermodynamic laws that rule out backstop technologies, too!

All in all, the constraints provided by thermodynamic analysis reveal important energy-related limits to growth. But a neoclassical environmental economics thus complemented still suffers from the negligence of complexity and time because the entropy law as such is not—and, due to the mechanical character of neoclassicism, cannot—be included. As the basic normative elements of the neoclassical hard core remain the same, the problematic implications of thermodynamic analysis for the welfare of future generations must be suppressed by absurdities like the backstop technology.

It is not surprising, in the face of these defects, that many energy analysts have questioned the subordinate role of thermodynamic analysis which is only supposed to provide constraints for economics. Dismissing both a purely thermodynamic optimization as blatantly unrealistic and the usual economic optimization as hopelessly inadequate, they go for an uncertain middle course. For example, the minimal energy requirements are to be determined "within cost and environmental constraints." (van Gool and Kümmel, 1986, 90) Or certain meta-economic criteria are invoked: "other arguments are decisive, such as strategic independence of the nation, the trade balance, environmental limitations." (van Gool, 1980a, 439) On the whole, the critique of economic dominance remains vague and rather intuitive; a clear alternative is not offered. For this mess an insufficient understanding of the role of value in economics is responsible. Once an economic paradigm (neoclassicism) and, thus, its underlying value concept (mechanical utility) are accepted, it does not make any sense anymore to try to 'amend' the resulting values or to use alternative value concepts in certain cases—such as energy (van Gool, 1987).

4.2.1.3. The combination of the materials balance approach and thermodynamic analysis. Of course, the constraints of the materials balance approach (relating to matter) and those of thermodynamic analysis (relating to energy) may be combined (e.g. Ruth, 1993) so that economics can make use of the insights of both approaches. However, their insufficiencies concerning time, interdependencies and intergenerational justice still persist.

4.2.1.4. Georgescu-Roegen's 'fourth law of thermodynamics'. According to the laws of thermodynamics, it is energy that limits economic growth whereas the finiteness of matter is not a real problem; after all, complete recycling is possible, at least theoretically. But Georgescu-Roegen's 'fourth law of thermodynamics' categorically rules out even this theoretical possibility (e.g. Georgescu-Roegen, 1981, 53ff; Georgescu-Roegen, 1986a, 268; Georgescu-Roegen, 1987, 156). His vehement but rather intuitive arguments rest on a plethora of practical examples which are to show that

> [c]omplete recycling is impossible. (…) [M]aterial objects wear out in such a way that small particles (molecules) originally belonging to these objects are gradually dissipated beyond the possibility of being reassembled. (Georgescu-Roegen, 1981, 60).

Plausible as this reasoning may be, it only can illustrate the practical difficulties, or even the practical impossibility, of perfect recycling but can never 'prove' its theoretical impossibility. On the contrary, Georgescu-Roegen's 'fourth law' directly contradicts the first law which clearly implies the possibility of complete recycling (Ayres and Kneese, 1989, 103ff; Binswanger, 1992, 114f; Binswanger, 1993, 214; Hall et al., 1986, 144f).

4.2.2. Statistical thermodynamics

Statistical thermodynamics equates entropy with disorder and an increase in entropy with a decrease in order. This statistical conception of order (or disorder) is precisely defined and quantifiable. However, except for some rare cases, like ideal gases or dilute solutions, it does not correspond to the usual, intuitive notion of order. To avoid misunderstandings many natural scientists refrain from using the term 'order' in a thermodynamic context or, at least, apply it only to the aforementioned special cases (Brostow, 1972, 124f; Callen, 1985, 380; Erbrich, 1988, 138).

Economists are less cautious. Doubting the applicability of classical thermodynamics to economic problems, they often opt for statistical thermodynamics instead whose entropy concept is thought to be more relevant, more plausible and easier to operationalize (Ayres, 1978, 44; Faber et al., 1995, 96f; Faber and Proops, 1986, 304). Of course the entropy concepts of classical and statistical thermodynamics are equivalent; it is only that the latter lends itself to a misleading, seemingly straightforward interpretation: "[E]ntropy can be used as a measure of 'disorder'." (Faber and Wagenhals, 1988, 230) But this generalization to the intuitive, anthropomorphic concept of order is not possible (Ayres, 1994, 11f; Georgescu-Roegen, 1971, ch. 6; O'Connor, 1988, 12f; O'Connor, 1991, 100f). Nonetheless, some approaches in environmental economics have been based on this general identification of entropy with disorder—most notably those of Faber and his co-authors who tried to build a unified analysis of resource and externality problems on it.

As regards resources, Faber et al. (1995) intend to use the entropy concept to extend the conventional materials balance approach in order to take not only the quantities of resources but also their concentrations into account. To this end high (low) concentrations are interpreted as orderly (disorderly) and assigned low (high) amounts of entropy (Faber et al., 1995, 3f). The resource extraction process consists of two steps: firstly, the matter containing the desired resource has to be mined ('appropriation'[9]); secondly, the resource itself has to be separated from the remainder of the base material ('separation'). 'Appropriation' is described in a non-thermodynamic way; the amount of energy required for the mining of one mole of base material is assumed to be a constant so that, obviously, there is an inverse linear relation between the energy required per mole of the resource and its concentration. In contrast, 'separation' is modelled analogously to the (reversible) unmixing of ideal, non-interacting gases. Accordingly, separating the resource from the waste matter is accompanied by a decrease in entropy—the negative of the increase in entropy which would result from the mixing of two ideal gases. From the entropy decrease a corresponding energy requirement is deduced which varies inversely with

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[9] 'Appropriation' here is used in a technical, not in a legal sense (see Section 4.1).

the concentration of the resource. The same goes, of course, for the total energy requirement, i.e. the sum of the energies necessary for 'appropriation' and 'separation'. As it is assumed that deposits of high concentration are mined first, two inverse relations result—one between resource concentration and energy requirement and one between resource concentration and the quantity of resources already extracted—which are (as additional constraints) integrated into a basically neoclassical welfare maximizing model.

What are the merits of this approach? Most obviously, the resulting energy requirements are unrealistically low because resources are not ideal, non-interacting gases (e.g., Fe_2O_3 cannot be simply 'unmixed' but has to be reduced to pure iron) and because resource extraction in reality has to make use of non-ideal, irreversible processes (O'Connor, 1988, 20ff). The authors themselves acknowledge the quantitative inadequacy of their approach but maintain that important qualitative insights are still possible (Faber, 1985, 328; Faber and Wagenhals, 1988, 241). But also these are rather dubious because of the interpretation of resources as ideal gases: firstly, resources are thus characterized merely by their concentration which, although important, is only secondary to their physical and chemical qualities (O'Connor, 1988, 19f). Secondly, energy resources are treated just like any other resource; their inevitable degradation in entropy-producing processes is neglected or even, in the description of resource separation as reversible unmixing, excluded. That is why there are no real limits to growth and the problem of intergenerational equity can be ignored. In fact, despite the authors' claims to the contrary, their approach does scarcely improve upon the materials balance approach: it makes use of only a negligible aspect of the entropy law, the entropy of mixing; its main implication is the increase in energy required for resource extraction when the resource concentration decreases—a standard assumption of neoclassical resource economics that can be plausibly justified without any recourse to the entropy law.

Also, for the problems of environmental pollution an entropy-based analysis is offered. Pollution is equated with deviations from ecological equilibrium which is—identifying entropy with disorder—interpreted as the constancy of environmental entropy (Faber et al., 1995, 100f). To quantify environmental degradation, i.e. entropy increases in the environment, Kümmel's pollution and damage functions are introduced (Kümmel, 1980, 24ff; Kümmel, 1986, 1019ff; Kümmel, 1989, 175ff; Kümmel and Schüssler, 1991). The pollution function defines the increase in entropy according to statistical thermodynamics as the increase of the number of microstates accessible to the polluting particles in the environment; as interactions between particles are ruled out, the entropy increases for the various kinds of particles can simply be summed up to get the total entropy increase. This increase is then directly translated into the consequent damage to human society (either in terms of production or welfare losses) by way of the damage function, which itself is not deduced from thermodynamics, but is rather arbitrarily postulated on the basis of some plausibility considerations. Both pollution and damage function were adopted almost unaltered by Faber and his co-authors who used them to complement their optimizing model.

But is its externality part more successful than its resource part? Unfortunately not. First of all, the aim of constant environmental entropy is highly questionable. Constant entropy is only a necessary, not a sufficient condition for an ecological equilibrium because severe ecological disruptions may occur with the overall entropy unchanged. Furthermore, such an equilibrium (or constant environmental entropy) may not be desirable in the first place: nonlinear thermodynamics has shown that evolution towards more complexity or 'higher order' can, and probably will, proceed while entropy is increased; and these evolutionary changes may, although disturbing any static equilibrium, be actually seen as an improvement from the human point of view (O'Connor, 1988, 25f; O'Connor, 1991, 102f). Secondly, even if the aim of constant environmental entropy is dropped, there are major problems with the pollution and the damage functions themselves and the role of entropy as an indicator of environmental quality. It is true, but trivially so, that pollution increases the entropy of the environment. But the proposed functions go much further in that they postulate a direct relation between entropy increase, environmental pollution and damage. This is, however, unwarranted: on the one hand, the pollution function captures but a small part of the actual entropy increase because the all-important interactions between particles are neglected; "with many pollutants, concentration effects per se are only secondary factors in the impact for better or for worse of different pollutants." (O'Connor, 1988, 27) On the other hand, it seems to be impossible for any single physical indicator to appropriately reflect all the different consequences of the multitude of pollutants because

> …different types of pollutants have very different significance in their impacts for human interests; (…) scientists often do not yet know what effects particular pollutants might have; (…) synergetic interactions between different pollutants are of critical importance in many situations; (…) many effects are very situation-specific; (…) the relevant time-scales of cumulative effects are variable and uncertain (O'Connor, 1991, 111).

Therefore, the entropy approach to environmental pollution does not even result in sensible qualitative statements—let alone exact quantitative ones.[10]

Although Faber and his colleagues realized the defects of neoclassical environmental economics and the importance of thermodynamics, they did not succeed in effectively incorporating the entropy law into environmental economics. It is not difficult to see why. They were moving inside the neoclassical world. True, neo-austrian capital theory was imported which allowed a more realistic description of the production process. But the basic ingredients of the neoclassical hard core remained untouched—ingredients with which thermodynamics can only be reconciled if the main implications of the entropy law, above all irreversibility, are suppressed by interpreting entropy exclusively as a measure of 'order'.

4.3. The energy theory of value

The attempts to create a 'natural' environmental economics simply by adding some thermodynamic constraints to the neoclassical hard core remain, as we have shown, quite unsatisfactory. Therefore, a new, non-mechanical economic paradigm seems to be called for. The energy theory of value looks like an obvious and promising alternative.[11] It goes beyond interdisciplinary cooperation or analogical reasoning in that it tries to explain economic phenomena exclusively or for the most part by the underlying energy flows; thus it is a variant of physical reductionism. Indeed, there are some who advocate the energy theory of value precisely because they see this reductionism as a worthy goal in itself (e.g., Zagoroff, 1954, 84). Most proponents of the energy theory of value, however, rely on the economic argument of the indispensability of energy. [Berry (1972), Costanza (1980, 1981, 1982), Costanza and Herendeen (1984), Gilliland (1975), Hannon (1973a,b, 1981), Odum (1971, 1973, 1978, 1983, 1984), Odum and Odum (1981), Slesser (1975).] This argument motivates energy analysis, too, and for many energy analysts the transition from positive energy analysis, especially energy accounting, to the normative energy theory of value has seemed like a small and, indeed, necessary step.

Now, what does an energy theory of value mean? Being the 'ultimate resource', energy is considered the sole determinant of the value of goods—with energy understood as 'embodied en-

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[10] In general, the same critique applies to similar one-dimensional indicators of environmental quality based on the materials balance approach (d'Arge, 1972, 16f; d'Arge and Kogiku, 1973, 62f) or on thermodynamic analysis (Edgerton, 1979, 1155f; Szargut, 1980, 717).

[11] The energy theory of value is the economic part of social energetics, an approach that interprets human society in terms of energy (Adams, 1975, 1982, 1988; Cottrell, 1970). Social energetics, in turn, originated from energetics, a 19th-century school of thought that postulated energy as the exclusive explanatory variable for all phenomena (its advocates included Helmholtz, Joule, Mayer and Rankine); this idea was first applied to nature only, but then quickly extended to the social sphere.

ergy', an energy accounting concept. Consequently, in a monetary economy prices have to be directly proportional to embodied energy, i.e. the energy-price ratio has to be the same for all goods. The energy theory of value belongs—its negligence of matter notwithstanding—to the substance theories of value because it interprets value as a 'substance' located within the goods. In one important respect it is similar to another substance theory of value—physiocratism: both know only one productive sector: agriculture in the case of physiocratism, the energy industry in the case of the energy theory of value.[12] Value can be created only insofar as energy is harnessed; it is the energy industry that exclusively performs this task by producing economically useful secondary energy from primary energy. Only making use of this secondary energy, all other sectors of the economy transform or 'materialize' value but create none of their own. It follows that profits are made only in the energy industry; in fact, it can be shown that for the firms of the energy sector maximizing the quantity of net energy is equivalent to maximizing profit (Huettner, 1976). For all other firms revenues equal costs by definition. The consumers, in the end, use up and destroy value. Sometimes short-term deviations from the general proportionality between energy content and price are conceded to bring the energy theory of value more in touch with reality (Berry, 1972, 9; Costanza and Herendeen, 1984, 157), but the explanations for these exceptions to the rule are rather vague and inconclusive. The energy theory of value having been postulated, the formulation of behavioural assumptions would have been the next step. Surprisingly, most energy value theorists remain silent on this point. Only Odum (1973, 222; 1978, 59ff; 1983, 492ff) offers some kind of behavioural assumptions, albeit only on a macro-economic level: he draws upon the two Lotka principles to explain and forecast the evolution of economic systems in terms of energy use. [The two principles were originally supposed to explain biological evolution from a thermodynamic point of view (Lotka, 1922): according to the first principle, evolution tends towards maximization of energy throughput or energy dissipation if energy is in ample supply. According to the second principle there will be evolutionary pressure towards higher energy efficiency as soon as there are energy shortages. The economic interpretation is straightforward, although Lotka himself never applied his principles to economics; in fact, he warned against expecting too much of them (Lotka, 1956, 357f).]

Is the energy theory of value able to replace the neoclassical value concept? No, it is not for a variety of reasons: firstly, the energy theory of value is beset with much the same technical problems as energy accounting. Secondly, production factors may be divided in flows (such as energy or materials) and funds (labour, capital and land); as only the former become 'embodied' in the goods the treatment of the latter is by no means obvious. If funds are neglected, their prices must be zero—an economically absurd result (Georgescu-Roegen, 1979a, 1048ff; Georgescu-Roegen, 1982, 23ff; Georgescu-Roegen, 1986a, 270ff). If they are taken into account, considerable valuation problems ensue. For example, which energy quantity is to be assigned to labour—the actual mechanical work done, the energy of the food intake or the energy embodied in the goods consumed? There is no clear-cut solution and the preference for the third alternative (Costanza, 1980, 1981; Costanza and Herendeen, 1984; Gilliland, 1978b, 102) seems to be due to merely pragmatic reasons. Similar problems are encountered in the cases of capital and land; in particular, interest as such must not exist (Alessio, 1981, 68f) and neither must a pure land rent. Not undisputed is, furthermore, the 'endogenization' of government services analogously to consumption (Costanza, 1980, 1981; Costanza and Herendeen, 1984). Thirdly, and most importantly, the energy theory of value is hardly able to explain anything because sensible behavioural assumptions do not and cannot exist. On the micro-economic level only the behaviour of firms in the energy sector can be explained by the profit maximization hypothesis. Neither the behaviour of other firms nor that of consumers can be accounted for because standard economic

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[12] Mostly the energy received directly through solar radiation is neglected; if it is included, then there are two productive sectors, energy industry and agriculture.

assumptions are inapplicable. And the hope that alternative assumptions might be derived from a micro-economic reinterpretation of the Lotka principles turns out to be delusive: again, the first Lotka principle implies profit maximization for the energy sector. For all other firms sales maximization and for all consumers maximization of consumption is implied—assumptions that are, at least in the consumer case, not totally implausible but that are hardly very useful. Things are similar in the case of the second Lotka principle: for energy firms the maximization of energy efficiency is tantamount to profit maximization, given a certain maximum input of primary energy (although it is difficult to account for this input limit). But for the rest of the economy the hypothesis of efficiency maximization is clearly unjustifiable (even if there were some limit on energy use). On the macro-economic level Odum's rendering of the Lotka principles cannot convince either: apart from the basic problem that the performance of economic systems can hardly be one-dimensionally explained by either energy use or energy efficiency, it is not clear when and how the transition from the first to the second principle is to be brought about. Thus, the explanatory value of the energy theory of value is extremely low; important economic phenomena must be left unaccounted for: for example, it is not at all possible to explain price changes of goods whose energy content remains the same (Hyman, 1980, 319f). Even from a purely environmental perspective the energy theory of value is unattractive because any recommendations for a responsible management of natural resources cannot be deduced from it. Energy value theorists tried to solve the problem of missing or inadequate behavioural assumptions by combining the energy with the utility theory of value. It is argued that the former applies on the macro level only whereas the latter determines micro-economic transactions (Costanza and Herendeen, 1984, 157; Odum, 1971, 204; Odum, 1983, 305). But this attempt to reconcile the alleged ecological plausibility with economic rationality is futile; it is based on an insufficient understanding of the meaning of value. Because of the central role value plays in economic theory there can be only one value concept. Assuming two value concepts is either redundant (if they are mutually dependent) or contradictory (if they are mutually independent, like energy and utility).

There is no way around it: the energy theory of value has to be bought at a very high price—because of its energetic determinism it has to negate completely the human element: no matter what men do, the results of their economic efforts are a function of energy only (Daly, 1981, 169ff; 1991b, 216f). That is why reasonable behavioural assumptions cannot exist and are, in fact, even superfluous. Because it gives rise to a lot of new problems without offering even halfway satisfactory solutions to the old ones, the energy theory of value has to be rejected. It is hopelessly inadequate as a fundament of economics and unable to help to establish a 'natural' environmental economics.[13]

> Value derives from the enjoyment of life, and there is more to life than energy, or even net energy or embodied energy. (Daly, 1981, 168).

But how then can some authors (Costanza, 1980, 1981; Costanza and Herendeen, 1984) possibly claim to have found empirical evidence for the energy theory of value? Their claims are based on an alleged uniformity of the energy-price ratio across the range of goods—which is what the energy theory of value would imply. However, as the customary energy accounting method of calculating embodied energies according to the monetary data of economic input–output statistics was used, this uniform ratio had to result necessarily. It is nothing but a methodological artefact and every theory of value can be 'proved' this way! In contrast, there are many quite obvious and straightforward observations that clearly disprove the energy theory of value—such as price changes unrelated to changes in embodied energy or the (inflation adjusted) secular decline of energy intensities in Western economies.

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[13] The same verdict also applies to a variant of the energy theory of value, the exergy theory of value, which is sometimes mistakenly called 'entropy theory of value' (Daly, 1968; Slesser, 1989).

4.4. Thermodynamic analogies

Being concerned with environmental economics, we stuck to the proper physical meaning of thermodynamic concepts so far—which does not seem to be the rule in economics: "outside of physical science the entropy concept has been lavishly applied to social systems." (Proops, 1987, 237). These thermodynamic analogies are, due to their often arbitrary and unjustified application, responsible for much of the confusion surrounding the role of thermodynamics in economics, which is why they at least have to be mentioned.

The best-known analogy doubtlessly is that between information and entropy [On the relation between thermodynamics and information theory see, e.g. Ayres (1994), ch. 2; Binswanger (1992), ch. I.5, I.6, Denbigh and Denbigh (1985), ch. 5 and Erbrich (1988), ch. III.3.] It was introduced by Shannon (1948), who constructed a measure for the potential information of a message which he called entropy because of its similarity (in fact, almost identity) with the entropy definition of statistical thermodynamics. Although natural scientists generally regard the analogy between informational and thermodynamic entropy to be merely formal [Denbigh and Denbigh (1985), ch. 5, Spreng (1984) and Wicken (1987), ch. 1; Wicken (1988), 141ff.], many economists—with Georgescu-Roegen (1977; 1987, 56), being a notable exception—interpret it in a material way. Furthermore, they tend to forget that 'information' in information theory is a purely technical notion and confound this 'syntactic' information with the 'semantic' or 'pragmatic' information (which refers to the meaning or the actual consequences of a message). This is why informational entropy has often been mistakenly applied to economics: entropy measures of economic information have been constructed, although the economically relevant information cannot sensibly be captured by measures based on Shannon's concept of information. The extent of economic information has been linked to the extent of the utilization of environmental services by the respective economy; from an environmental perspective, however, it does not matter how much information an economy contains but what it is used for (Binswanger, 1992, 150f). There is only one—rather trivial—material relation between entropy and information: like any other activity the processing of information has to make use of energy which, under non-ideal conditions, is dissipated so that entropy increases (Tribus and McIrvine, 1979). To avoid misunderstandings it is absolutely necessary to distinguish carefully between informational and thermodynamic entropy and between the different concepts of information.

Stochastic entropy is another purely formal analogy. According to the entropy concept of statistical thermodynamics it has been defined as a measure of statistical dispersion (Horowitz and Horowitz, 1976; Proops, 1987, 233f). Stochastic entropy has been widely applied in the analysis of economic data—as a measure, e.g., for income distribution or industrial concentration. In principle, there is no problem with it, but care has to be taken nonetheless. Firstly, stochastic entropy can only be calculated for probability distributions—not just for any sum of non-negative fractions that add up to unity. Secondly, the entropy law must, of course, not be invoked since there is no material relation between thermodynamics and stochastic entropy.

It is the attempts to construct a thermodynamic economics, however, that represent economic-thermodynamic analogies proper and that are therefore most important for economic theory. [Such analogies were formulated by, e.g., Ayres (1994, ch. 7), Bryant (1979, 1982, 1985), Davis (1941, 170), English (1974), Franksen (1972, 1974), Hufnagel (1995, ch. 4), Lichnerowicz (1971) and Pikler (1951).] Here, thermodynamics serves as a model for the construction of a new economic hard core—just as classical mechanics has been the model for neoclassical economics. By way of analogy, economic equivalents are postulated for thermodynamic quantities and the relations between the latter are imposed upon the former in the hope of gaining new economic insights. But this hope has been disappointed so far: whether micro-economic or macro-economic, whether elaborate or superficial—the attempts to build a thermodynamic economics for the most part have been economically sterile because of their arbitrary and unjustified execution. In order to avoid such purely formal, economically insubstantial exercises, economists have to be explicit about what they want to achieve and why they use thermodynamic analogies for their purpose. Only if this simple rule is observed can thermodynamic analogies have the potential for stimulating the development of economics. For example, Ayres (1994), ch. 7, recently suggested a promising thermodynamic analogy which may be helpful for a better understanding of economic dynamics. But in any case, thermodynamic analogies do not seem to be able to advance the cause of a more realistic environmental economics—which is not particularly surprising, though, given the non-environmental intentions behind these analogies.

4.5. Where do we go from here?

It looks like environmental economics is faced with a profound dilemma: on one hand, thermodynamics is highly relevant to environmental economics so that thermodynamic concepts seem to have to be integrated somehow to redress the deficiencies of neoclassical environmental economics. On the other hand, all approaches toward such an integration were found to be incomplete and unsatisfactory. On the basis of the neoclassical paradigm, thermodynamic constraints are able to take only the first law of thermodynamics into consideration whereas the implications of the entropy law cannot be given due regard. But the radical alternative of an energy theory of value was even more of a failure. And thermodynamic analogies are not helpful either—which they could not be expected to be anyway.

Still, "[w]hat we need to do is incorporate ecological theories that are based on thermodynamic considerations into economic theory." (Binswanger, 1993, 227), but how? In Section 5 we try to give a tentative answer.

5. Sustainability and value theory

How we find a way out of the dilemma just described? For one thing, we might continue to pursue the strategy still dominant in economics—the adoption of 'natural' value concepts, either in a reductionist or in an analogical way. But the imitation of the natural sciences is no panacea for economic problems. As the example of the energy theory of value has shown, reductionism is conceptually unable to account for basic human qualities, such as creativity, so that none of its possible variants can ever be an adequate basis for economics. Natural analogical reasoning is no solution to our dilemma either: in the case of thermodynamic analogies the clear failure of most attempts to produce economically interesting results does not bode well for this approach, although a breakthrough of course, cannot be completely ruled out. Anyway, thermodynamic analogies have given way to a merely metaphorical use of thermodynamic concepts which are drawn upon, above all, to illustrate the shortcomings of neoclassicism, but not to construct a serious alternative to it. The situation is only somewhat different in the case of biology. Although there are some promising analogical approaches to certain economic problems, a complete and consistent biological analogy to contest the position of the mechanical analogy is still to emerge; on the whole, biology, too, is predominantly referred to metaphorically (for an overview see Hodgson, 1993).

With reductionism and analogism thus de facto eliminated, interdisciplinary cooperation remains as the only possibility to integrate thermodynamic concepts into environmental economics. However, the neoclassical paradigm proved to be too restrictive for interdisciplinary cooperation to be very fruitful: positively, the negligence of time and of the complexity of economy–ecology interactions cannot be overcome; normatively, 'welfarism' and the dominance of efficiency considerations prevents an effective care for posterity. It is the normative problem that turns out to be decisive: the transfer of thermodynamic concepts into neoclassical environmental economics was found to be unsatisfactory mainly because of the demand for intergenerational justice. Although most neoclassicals accept this aim, no consequences are drawn for the normative elements of the neoclassical hard core. This normative inconsistency is highlighted by the thermodynamic constraints. If, on the other hand, the utilitarian position of neoclassical welfare economics is unreservedly accepted, then it would probably suffice to just add a few thermodynamic constraints to the usual models; the normative problem has become irrelevant and the remaining positive defects are not too serious anymore once the more remote future can safely be neglected—by way of the discounting of the welfare of future generations. Obviously, there is an intimate relation between the normative position and the integration of thermodynamic concepts: value decisions determine what an 'adequate' integration of thermodynamic concepts has to look like; and these concepts may illuminate problematic consequences of value decisions. That is why the transfer from thermodynamics to economics must be based on some kind of value decision. It is important for environmental economics that, first, this decision be made explicitly and, second, its consequences be accepted. The approaches to integrate thermodynamics into neoclassical economics could not but fail because none of these conditions was fulfilled—the focus was simply too narrow, exclusively economical.

In contrast, the most important alternative to neoclassical environmental economics, ecological economics, is based on an explicit value decision—the decision in favour of intergenerational justice. Ecological economics has pursued an ends-oriented approach and postulated the principle of sustainability from which to deduce an environmental economics untarnished by the neoclassical defects. Sustainability can only be justified on ethical and moral grounds—by recognizing the right of every generation to the integrity of the natural bases of life and the consequent duty of every generation to maintain the stock of 'natural capital' (at least insofar as it cannot be substituted for by man-made capital). [Bartelmus (1994), Daly (1990, 1992a), Hampicke (1992, ch. 5.3); Pearce and Turner (1990, 43ff); Tisdell (1993).] Therefore, sustainability itself is not 'founded' on thermodynamics—although its insights certainly did play a role when this aim was postulated. A specific environmental policy is indispensable because the market cannot be relied upon to provide sustainability. [Ayres (1991, 265, 271); Ayres (1994, 282ff); Binswanger (1993, 218); Daly (1991b, 201f); Daly (1992a, 1993, 374f); Georgescu-Roegen (1979b, 17f); Hampicke (1992, 421f); Hyman (1980, 322); Slesser (1993, 306).] Not only are there the usual public goods problems; more important, it is logically impossible for the market to fulfil this stabilizing task on its own: sustainability is not a good (not even a public good!) as it concerns the relation between economy and ecology and aims at the mutual stabilization of both systems (although the realization of sustainability can be regarded as a public good whose supply depends on collective action).

> The market mechanism is simply not the adequate level to deal with long-run environmental and exhaustion problems. (…) The steering function of prices is extremely important, but the direction to be headed for must be determined by other means. (Bruggink, 1985, 140).

What kind of policy is necessary to guarantee sustainability? In the face of unsurmountable physical limits, the fact of irreversibility and the high complexity of economy–ecology interactions, the economy has to be contained by absolute limits if it is to be sustainable; therefore, a macro-economic complement for the orthodox micro-economic environmental policy is necessary (Daly, 1991a,b, 1992a), which might include the protection of certain species and ecosystems, limits on energy and resource use, or a much more cautionary attitude towards technological progress.

Such an environmental economics is, at least in principle, able to eliminate the deficiencies of neoclassical environmental economics: sustainability explicitly pays attention to intergenerational justice which, after all, is its prime motivation. And the macro-economic environmental policy may take all the crucial, hitherto neglected issues into account—with the help of thermodynamics (and other natural sciences). The role thermodynamics has to play in this context is quite different from that of rigid neoclassical constraints; thermodynamic insights are to be incorporated in a flexible way. The concept of irreversibility may serve as a leitmotiv for maintaining biodiversity and dealing with new technologies; on a more practical level thermodynamics may be drawn upon to establish thermodynamic limits and make realistic energy consumption forecasts. However, it certainly will not be possible to 'deduce' an 'optimal' environmental policy from thermodynamic principles—thermodynamics cannot replace genuinely economic and political decisions.

Therefore, both extreme positions in the 'thermodynamic controversy', i.e. the insistence on the total irrelevance of thermodynamics and the belief in 'thermodynamic solutions' for all economic problems, have to be given up in favour of an important but limited role for thermodynamics in environmental economics. Hopefully, the thermodynamic controversy can be settled in this way because now there are more important tasks on which to concentrate research efforts—above all the operationalization of sustainability and the required macro policy.

But we also have to turn to the problem of the economic foundation of the proposed 'natural' environmental economics. Is the macro policy compatible with the neoclassical basis? At first sight this does not seem to be a problem at all because it looks like we could simply accept the components of the macro policy as political decisions outside the realm of economics—just as, on the micro level, the charges-and-standards approach takes environmental standards as given. However, this pragmatic solution is not possible: firstly, the explanatory range of neoclassical environmental economics would be narrowed still further. One may indeed doubt whether it would deserve its name at all if it has to relegate not only micro-economic but also macro-economic environmental policy to politics and thus declares itself unable to say anything about vital environmental issues (Weimann, 1987, 317). Secondly, the macro policy is conceptually incompatible with the neoclassical paradigm because it can be justified only by the appeal to rights and duties whereas neoclassicism relies exclusively on utility considerations. Also in environmental economics the microfoundations of macro-economics are missing. It is clear that this inconsistency not only is theoretically unsatisfactory but also makes a coherent and consequent environmental policy difficult to devise and implement. This inconsistency is attributable to the limitedness of the neoclassical value concept, utility, which—due to its teleological character (welfarism)—cannot accommodate deontological considerations.

While processes may end up getting some indirect attention insofar as they influence people's utilities, nevertheless no direct and basic importance is attached in the utilitarian framework to rights and liberties in the evaluation of states of affairs (Sen, 1995, 13).

Welfarism, in turn, is but one—albeit an important—aspect of a more general problem—the incapability of neoclassicism to pay due attention to the social aspects of the economy. Because of its mechanistic and individual value concept neoclassical economics acknowledges only 'social' qualities of certain goods, public goods, that are to be supplied collectively. But the valuation of goods in general and the coordination of economic decisions in the case of private goods are conceived of as purely individual. However, not only are perfectly private goods very rare, both valuation and decision coordination cannot be separated from their social context (Hodgson, 1988).[14] Apparently, the value concept of neoclassical economics diverges considerably from the practical value concept pervading and guiding actual economic life. That is why a social reconstruction of economics is necessary. It has been advocated by socio-economics in recent years (Etzioni, 1988). But until now, a serious alternative to neoclassical economics is not yet in sight; socio-economics is still in its very first stages. And it is doubtful whether things will change for the better unless a new, a social value theory is postulated which is indispensable as the centerpiece of this new economics. The most interesting sketch of a possible social theory of value is due to Mirowski (1990, 1991, 1994), whose approach is based on the social institution of money.

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[14] We do not advocate collectivism. Of course, all social phenomena result from individual actions. This ontological individualism leads to methodological individualism which we adhere to, too. But individualism does not imply the negligence of interindividual relations.

Surprisingly, a consistent and complete 'natural' environmental economics has to be part of a 'social' environmental economics because crucial social, political and, above all, moral issues must not be excluded, and because a social economics, not being copied from any particular concept of the natural sciences, will be able to take into account all the economically relevant insights of the natural sciences. Of course, neoclassical economics and its concepts are not to be completely thrown overboard; they will be still very useful for the solution of a lot of economic problems and have to be integrated into the wider social paradigm.

These speculations admittedly give rise to more questions than they answer; they have to be understood primarily as suggestions for further research.

Nonetheless, we are now able to answer our introductory question of what role thermodynamics ought to play in environmental economics. Firstly, thermodynamics has a heuristic function in that it serves to highlight the shortcomings of not only neoclassical environmental economics but neoclassical economics in general. Secondly, and most important, there is a conceptual function for thermodynamics: it helps to justify the concept of sustainability and thus the inclusion of rights and duties into economic analysis. This, in turn, leads to the demand for a social reconstruction of economics on the basis of a social theory of value. Thirdly, thermodynamics also has an analytical function: for the operationalization of sustainability, i.e. the elaboration of the details of macro-economic environmental policy, thermodynamic concepts are indispensable in order to derive the necessary assumptions about substitution possibilities and technological progress.

Thus, although thermodynamics definitely cannot solve all the problems of economics, or even of environmental economics, it has some very important contributions to make.

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