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# 6. Thermodynamic Models

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## 6.1 INTRODUCTION

Integrating methods and models from thermodynamics and from economics promises to yield encompassing insights into the nature of economy-environment interactions. The division of labour between thermodynamics and economics seems to be obvious. Thermodynamics should provide a description of human societies' physical environment, while economics should provide an analysis of optimal individual and social choice under environmental scarcities.

But the task is difficult. Being a branch of physics, thermodynamics is a natural science. It explains the world in a descriptive and causal, allegedly value-free manner. On the other hand, economics is a social science. While it pursues to a large extent descriptive and causal (so-called 'positive') explanations of social systems, it also has a considerable normative dimension. Valuation is one of its basic premises and purposes. Bringing together thermodynamics and economics in a common analytical framework therefore raises all kinds of questions, difficulties and pitfalls.

This chapter lays out the rationale, concepts, and caveats for developing and using thermodynamic models in ecological economics. Section 6.2 sketches the historical origins of this endeavour. Section 6.3 develops the fundamental rationale of employing thermodynamic concepts and models in ecological economics. Section 6.4 briefly introduces the elementary concepts and laws of thermodynamics. Section 6.5 gives an overview of different approaches to incorporating thermodynamic concepts into economic analysis, and assesses their respective potential for ecological economics. Section 6.6 surveys various implications and insights from thermodynamic models in ecological economics. Section 6.7 concludes by assessing the role of thermodynamics for ecological economics, and for the discussion of sustainability.

## 6.2 HISTORICAL ORIGINS

The origins of thermodynamics are in the nineteenth century when practitioners, engineers and scientists like James Watt (1736–1819), Sadi Carnot (1796–1832), James Prescott Joule (1818–1889), Rudolph Clausius (1822–1888) and William Thomson (the later Lord Kelvin, 1824–1907) wanted to understand and increase the efficiency at which steam engines perform useful mechanical work. From the very beginning, this endeavour has combined the study of natural systems and the study of engineered systems – created and managed by purposeful human action – in a very peculiar way, which is rather unusual for a traditional natural science such as physics.

Not surprisingly then, the laws of thermodynamics were found by economists to be concepts with considerable implications for economics.[1] For instance, economists like Kenneth Boulding (1966), Robert Ayres and Allen Kneese (1969), and Nicolas Georgescu-Roegen (1971) turned to thermodynamics when they wanted to analyse economy-environment interactions in an encompassing way, and analytically root the economy in its biogeophysical basis.

In a first step, the Materials Balance Principle was formulated based on the thermodynamic Law of Conservation of Mass (Boulding, 1966; Ayres and Kneese, 1969; Kneese et al., 1972). In view of this principle, all resource inputs that enter a production process eventually become waste. By now, this is an accepted and undisputed piece of resource, environmental and ecological economics.

At the same time, Georgescu-Roegen (1971) developed an elaborate and extensive critique of economics based on the laws of thermodynamics, and in particular the Entropy Law, which he considered to be ‘the most economic of all physical laws’ (Georgescu-Roegen, 1971, p. 280).[2] His contribution initiated a heated debate on the question whether the Entropy Law – and thermodynamics in general – is relevant to economics (Burness et al., 1980; Daly, 1992; Kåberger and Månsson, 2001; Khalil, 1990; Lozada, 1991; 1995; Norgaard, 1986; Townsend, 1992; Williamson, 1993; Young, 1991; 1994).[3] While Georgescu-Roegen had, among many other points, formulated an essentially correct insight into the irreversible nature of transformations of energy and matter in economies, his analysis is to some extent flawed by wrongly positing what he calls a ‘Fourth Law of Thermodynamics’ (Ayres, 1999). [4] It may be for this reason that the Second Law and the entropy concept have not yet acquired the same undisputed and foundational status for resource, environmental and ecological economics as have the First Law and the Materials Balance Principle.

But as Georgescu-Roegen’s work and the many studies following his lead have shown, the Entropy Law, properly applied, yields insights into the irreversible nature of economy-environment interactions that are not available otherwise (Baumgärtner et al., 1996). Both the First and the Second Laws of Thermodynamics therefore need to be combined in the study of how natural resources are extracted, used in production, and give rise to emissions and waste, thus leading to integrated models of ecological-economic systems (e.g. Baumgärtner, 2000a; Faber et al., 1995; Perrings, 1987; Ruth, 1993; 1999).

## 6.3 FUNDAMENTAL RATIONALE

### 6.3.1 Different Perspectives on Economy-Environment Interactions

When economists started to analyse the flow of resources, goods, services and money in an economy, the picture was rather simple: there are two groups of economic agents, consumers and producers; producers deliver goods and services to consumers, and consumers give the resources with which they are endowed, labour in particular, to producers. Thus, there is a circular flow of commodities in an economy. There is an equivalent circular flow of money counter to that primary flow, as consumers pay money to producers for the goods they consume, and producers remunerate the labour force they receive from the consumers/labourers.[5]

Since the two corresponding flows, the primal flow of real commodities and the dual flow of monetary compensation, are exactly equivalent, it seems superfluous to always study both of them when analyzing economic transactions and allocations. Hence, the convention was established in economics to exclusively consider the monetary flow. The current system of national economic accounts, which is meant to be a full representation of economic activity in an economy over one time period, therefore captures all transactions in monetary units, e.g. the provision of labour and capital, the trading of intermediate goods and services between different sectors of the economy, and final demand for consumer goods.

Of course, this picture is too simple, as it neglects the use of natural resources and the emission of pollutants and wastes. Both activities are a necessary aspect of economic action. In the early nineteenth century, the subdiscipline of environmental and resource economics emerged to deal with the question of how to take into economic account the use of natural resources on the one hand and the emission of pollutants and wastes on the other (Gray, 1913, 1914; Pigou, 1912/1920; Hotelling, 1931). The picture now appeared as follows: there is a circular flow – actually: two equivalent circular flows – between consumers and producers which form the core of economic activity. In addition, there is an inflow of natural resource and an outflow of emissions and wastes. Thus, a linear throughflow of energy and matter drives the circular flow of economic exchange.

One conceptual problem from the very beginning of environmental and resource economics is the following. While the description of economic activity is generally in monetary terms, the inflow of natural resources as well as the outflow of emissions and wastes does not have an obvious value dimension. Although an obvious fact in real terms, it is very difficult to capture in monetary terms, as there are normally no markets for these flows, such that they do not carry an obvious price tag. But taking these flows into economic account – based on the understanding that economics analyses transactions in monetary terms – requires monetarisation of these flows. As a consequence, valuation of environmental goods, services and damages became a major challenge. The aim was to complement the real dimension of these flows with the corresponding (dual) value dimension.

A further step in the development of ecological-economic thinking was the insight that the inflow of natural resources (resource economics) and the outflow of emissions and wastes (environmental economics) are not independent. Obviously, these two flows are linked by economic activity; i.e., economic activity transforms natural resources into emissions and wastes. But these two flows are also linked because they originate and terminate in the natural geobiophysical environment. For example, environmental pollutants released into natural ecosystems may impair the ecosystems' ability to produce the ecosystem goods and services, e.g., timber or fish, which are then used as a natural resource by the economy. This means, the extraction of natural resources, the production of goods and services within the economy, as well as the emission of pollutants and wastes all happen within the system of the natural geobiophysical environment.

This is the 'vision' (in the sense of Schumpeter)[6] of ecological economics: ecological economics views the human economy as an open subsystem of the larger, but finite, closed, and non-growing system of non-human nature (Boulding, 1966; Georgescu-Roegen, 1971; Daly, 1977; Ayres, 1978; Faber and Proops, 1990; and many more). In this view, the human economy is a part of nature. In contrast, in the view of traditional environmental and resource economics, Nature is treated as a part of the human economy. Both 'Resources' and 'Environment' are treated as additional economic sectors in the system of national economic accounts, and flows to and from these sectors are accounted for in monetary units.

The change of perspective from 'nature as part of the economy' to 'the economy as part of nature' amounts to a scientific revolution not unlike the transition from the heliocentric to the geocentric world view in the Copernicanean revolution (Brown, 2001).

### 6.3.2 Duality Between the Real and Monetary Descriptions and the Role of Thermodynamics

As we have seen, economic analysis, including environmental and resource economics, is based on the idea of duality between the flow of real commodities and services (measured in physical units) and an equivalent value flow (measured in monetary units), and consequently focuses solely on the value dimension. But as far as the throughflow of energy and matter through the economy is concerned, the value of this flow is far from obvious. Markets cannot give the values we are looking for, as markets typically do not exist in this domain. And where they exist, the resulting values are distorted due to ubiquitous externalities and public goods.

As a consequence, the valuation of natural goods and services has to be set up explicitly as a non-market process, and elaborate theories and techniques have been proposed for this purpose.[7] All these techniques require, to a greater or lesser extent, an adequate, prior description in real terms of the particular commodity or service to be valued. In other words, before individuals or society can value something, they have to have a pretty good idea about what exactly that something is. This holds, in particular, for the energy and material resources used in production as well as for the emissions and wastes generated as by-products of desired goods.

Here lies the relevance of thermodynamics. Being the branch of physics that deals with transformations of energy and matter, thermodynamics is an appropriate natural science foundation for providing a description in real terms of what goes on when human societies interact with the non-human environment. In particular, thermodynamics captures the energy/matter-dimension of economy-environment interactions. Thus, it is a necessary complement and prerequisite for economic valuation.

## 6.4 CONCEPTS AND LAWS OF THERMODYNAMICS

Thermodynamics is the branch of physics that deals with macroscopic transformations of energy and matter. Briefly summarized, the fundamental concepts and laws of phenomenological thermodynamics can be stated as follows.[8]

### 6.4.1 Systems and Transformations

With respect to the potential exchange of energy and matter between the inside and the outside of the system under study, one distinguishes between the following types of thermodynamic system:

- *Isolated* systems exchange neither energy nor matter with their surrounding environment.
- *Closed* systems exchange energy, but not matter, with their surrounding environment.
- *Open* systems exchange both energy and matter with their surrounding environment.

A system is said to be in *thermodynamic equilibrium* when there is complete absence of driving forces for change in the system. Technically, the various potentials of the system are at their minimum, such that there are no spatial variations of any of the intensive variables within the system. *Intensive* variables are quantities which do not change when two separate but identical systems are coupled. In contrast, *extensive* variables are quantities whose value for the total system is simply the sum of the values of this quantity in both systems. For example, temperature and pressure are intensive variables while mass and volume are extensive ones. As long as there are spatial variations in, say, temperature within a system, it is not yet in thermodynamic equilibrium, but there exists a potential for change. The equilibrium state is characterized by a uniform temperature throughout the system.

Consider an isolated system which undergoes a transformation over time between some initial equilibrium state and some final equilibrium state, either by interaction with its environment or by interaction between different constituents within the system. If the final state is such that no imposition or relaxation of constraints upon the isolated system can restore the initial state, then this process is called *irreversible*. Otherwise the process is called *reversible.* For example, at some initial time a gas is enclosed in the left part of an isolated box; the right part is separated from the left part by a wall and is empty. Now, the separating wall is removed. The molecules of the gas will then evenly distribute themselves over the entire volume of the box. The thermodynamic equilibrium of the final state is characterized by a uniform density of molecules throughout the entire volume. Reintroducing the wall into the isolated system separating the left part from the right half would not restore the initial state of the system. Nor would any other imposition or relaxation of constraints on the isolated system be able to restore the initial state. Therefore, the transformation given by the removal of the wall is an irreversible transformation of the isolated system.[9] Generally, a process of transformation can only be reversible if it does not involve any dissipation of energy, such as through e.g., friction, viscosity, inelasticity, electrical resistance or magnetic hysteresis.

### 6.4.2 The Fundamental Laws of Thermodynamics

The *First Law of Thermodynamics* states that in an isolated system (which may or may not be in equilibrium) the total internal energy is conserved. This means that energy can be neither created nor destroyed. However, it can appear in different forms, such as heat, chemical energy, electrical energy, potential energy, kinetic energy, work, etc. For example, when burning a piece of wood or coal the chemical energy stored in the fuel is converted into heat. In an isolated system the total internal energy, i.e. the sum of energies in their particular forms, does not change over time. In any process of transformation only the forms in which energy appears change, while its total amount is conserved.

Similarly, in an isolated system the total mass is conserved (*Law of Conservation of Mass*). Obviously, if matter cannot enter or leave an isolated system, the number of atoms of any chemical element within the system must remain constant. In an open system which may exchange matter with its surrounding, a simple *Materials Balance Principle* holds: the mass content of a system at some time is given by its initial mass content plus inflows of mass minus outflows of mass up to that point in time. The law of mass conservation, while often regarded as an independent conservation law besides the law of energy conservation, is actually an implication of the First Law of Thermodynamics. According to Einstein's famous relation $E=mc^2$ mass is a form of energy, but mass can only be transformed into non-material energy, and vice versa, in nuclear reactions. Therefore, neglecting nuclear reactions it follows from the First Law of Thermodynamics that mass and non-material energy are conserved separately.

In any process transforming energy or matter, a certain amount of energy is irrevocably transformed into heat. The variable *entropy* has been defined by Rudolph Clausius (1854; 1865) such as to capture this irrevocable transformation of energy: if a certain amount of heat $\mathrm{d}Q$ is reversibly transferred to or from a system at temperature $T$, then $\mathrm{d}S = \mathrm{d}Q/T$ defines the change in entropy $S$. Clausius showed that $S$ is a state variable of the system, i.e., it remains constant in any reversible cyclic process and increases otherwise. The *Second Law of Thermodynamics*, the so-called Entropy Law, states the unidirectional character of transformations of energy and matter: With any transformation between an initial equilibrium state and a final equilibrium state of an isolated system, the entropy of this system increases over time or remains constant. It strictly increases in irreversible transformations, and it remains constant in reversible transformations, but it cannot decrease.

Entropy, in this view, can be interpreted as an indicator for the system's capacity to perform useful work. The higher the value of entropy, the higher the amount of energy already irreversibly transformed into heat, the lower the amount of free energy of the system and the lower the system's capacity to perform work. Expressed the other way round, the lower the value of entropy, the higher the amount of free energy in the system and the higher the system's capacity to perform work. Hence, the statement of the Second Law of Thermodynamics amounts to saying that, for any process of transformation, the proportion of energy in the form of heat to total energy irreversibly increases or remains constant, but certainly never decreases. In other words, with any transformation of energy or matter, an isolated system loses part of its ability to perform useful mechanical work and some of its available free energy is irreversibly transformed into heat. For that reason, the Second Law is said to express an irreversible degradation of energy in isolated systems over time. At the same time, the economic relevance of the Second Law becomes obvious.

While the notion of entropy introduced to phenomenological thermodynamics by Clausius is based on heat, Ludwig Boltzmann (1877) introduced a formally equivalent notion of entropy that is based on statistical mechanics and likelihood. His notion reveals a different interpretation of entropy and helps to show why it irreversibly increases over time. Statistical mechanics views gases as assemblies of molecules, described by distribution functions depending on position and velocity. This view allows the establishment of connections between the thermodynamic variables, i.e., the macroscopic properties such as temperature or pressure, and the microscopic behaviour of the individual molecules of the system, which is described by statistical means.[10] The crucial step is to distinguish between microstates and macrostates of a system. The *microstate* is an exact specification of the positions and velocities of all individual particles; the *macrostate* is a specification of the thermodynamic variables of the whole system.

Boltzmann assumed that all microstates have equal *a priori* probability, provided that there is no physical condition which would favour one configuration over the other. He posited that every macrostate would always pass to one of higher probability, where the probability of a macrostate is determined by the number of different microstates realizing this macrostate. The macroscopic thermal equilibrium state is then the most probable state, in the sense that it is the macrostate which can be realized by the largest number of different microstates. Boltzmann defined the quantity Ω, counting the number of possible microstates realizing one macrostate, and related this to the thermodynamic entropy $S$ of that macrostate. He used $S = k \log \Omega$, with $k$ as a factor of proportionality called Boltzmann's constant. Entropy can thus be taken as a measure of likelihood: highly probable macrostates, that is macrostates which can be realized by a large number of microstates, also have high entropy. At the same time, entropy may be interpreted as a measure of how orderly or mixed-up a system is. High entropy, according to the Boltzmann interpretation, characterizes a system in which the individual constituents are arranged in a spatially even and homogeneous way ('mixed-up systems'), whereas low entropy characterises a system in which the individual constituents are arranged in an uneven and heterogeneous way ('orderly systems'). The irreversibility stated by the Second Law in its phenomenological formulation (in any isolated system entropy always increases or remains constant) now appears as the statement that any isolated macroscopic system always evolves from a less probable (more orderly) to a more probable (more mixed-up) state, where $\Omega$ and $S$ are larger.

Whereas the Second Law in its Clausius or Boltzmann formulation makes a statement about isolated systems in thermodynamic equilibrium only, the study of closed and open systems far from equilibrium has shown (Prigogine, 1962; 1967) that entropy is also a meaningful and useful variable in closed and open systems. Any open system is a subsystem of a larger and isolated system. According to the conventional formulation of the Second Law the entropy of the larger and isolated system has to increase over time, but the entropy of any open subsystem can, of course, decrease. Viewing open systems as subsystems of larger and isolated systems reveals, however, that an entropy decrease in an open subsystem necessarily has to be accompanied by an entropy increase in the system's environment, that is the rest of the larger, isolated system, such that the entropy of the total system increases.

A generalization of the Second Law is possible such that it refers not only to isolated systems. Irrespective of the type of thermodynamic system under study, and irrespective of whether the system is in thermodynamic equilibrium or not, it is true that entropy cannot be annihilated; it can only be created (Falk and Ruppel, 1976, p. 353). This more general, system independent formulation of the Second Law implies the usual formulations for isolated systems. The relevance of the system independent formulation of the Second Law lies in the fact that most real systems of interest are not isolated but closed or open. Hence, the latter formulation is the form in which the Second Law is apparent in everyday life.

### 6.4.3 Quantification and Application

The entropy concept is essential for understanding how resource and energy scarcity, as well as the irreversibility of transformation processes, constrain economic action (Georgescu-Roegen, 1971; Baumgärtner 2003a). However, it is a very abstract concept and it is notoriously difficult to apply in specific contexts. One of the complications is due to the fact that a system's capacity to perform work depends not only on the state of the system, but also on the state of the system's environment. Therefore, for applications of the fundamental thermodynamic insights in the areas of mechanical and chemical engineering, as well as in economics, it is useful to relate the system's ability to perform work to a certain standardized reference state of its environment. *Exergy* is defined to be the maximum amount of work obtainable from a system as it approaches thermodynamic equilibrium with its environment in a reversible way (Szargut et al., 1988, p. 7). Exergy is also commonly called *available energy* or *available work* and corresponds to the 'useful' part of energy, thus combining the insights from both the First and Second Laws of Thermodynamics. Hence, exergy is what most people mean when they use the term 'energy' carelessly, e.g., when saying that 'energy is used' to carry out a certain process.

The relationship between the concepts of entropy and exergy is simple, as $W_{\text{lost}} = T_0 S_{\text{gen}}$ (*Law of Gouy and Stodola*), where $W_{\text{lost}}$ denotes the potential work or exergy lost by the system in a transformation process, $T_0$ denotes the temperature of the system's environment, and $S_{\text{gen}}$ denotes the entropy generated in the transformation. This means, as the system's entropy increases as a consequence of irreversible transformations according to the Second Law, the system loses exergy or some of its potential to perform work. Exergy, unlike energy, is thus not a conserved quantity. While the entropy concept stresses that with every transformation of the system something useless is created, the exergy concept stresses that something useful is diminished. These developments are two aspects of the same irreversible character of transformations of energy and matter.

As the system might consist simply of a bulk of matter, exergy is also a measure for the potential work embodied in a material, whether it is a fuel, food or other substance (Ayres, 1998; Ayres et al., 1998). The exergy content of different materials can be calculated for standard values specifying the natural environment, by considering how that material eventually reaches thermodynamic equilibrium with its environment with respect to temperature, pressure, chemical potential and all other intensive variables.[11] Taking a particular state of the system's environment as a reference point for the definition and calculation of exergy may be considered as a loss of generality as compared to the entropy concept. However, this referencing seems to be permissible since all processes of transformation – be it in nature or in the economy – are such that:

- all the materials involved eventually do reach thermodynamic equilibrium with the natural environment; and
- the environment is so large that its equilibrium will not be affected by the particular transformation processes under study.

While both the entropy and the exergy concept yield the same qualitative insights into the fundamentally irreversible character of transformations of energy and matter, the exergy concept is more tangible, as it is directly related to the very compelling idea of 'available work' and it can be more easily quantified than entropy.

## 6.5 DIFFERENT APPROACHES

How can thermodynamic concepts, laws and results be incorporated in a fruitful manner into economic analysis? This has been attempted in basically four ways,[12] which are very different in the intellectual approach they take. In the following, I shall describe each of them in detail and assess their potential for ecological economics.

### 6.5.1 Isomorphism of Formal Structure

Both thermodynamics and economics can formally be set up as problems of optimization under constraints. For example, equilibrium allocations in an economy can be viewed as a result of the simultaneous utility maximization under budget constraints of many households and profit maximization under technological constraints of many firms. Likewise, equilibrium micro- or macrostates of a thermodynamic system can be derived from the minimization of a thermodynamic potential, such as, e.g., Helmholtz or Gibbs free energy, under the constraints of constant pressure, volume, chemical potential etc. The mathematical structure of both economic and thermodynamic problems, thus, is formally equivalent. There is an isomorphism between the two types of problems and their respective solutions.

As a consequence, one may exploit this formal isomorphism to obtain insights into the structure of economic equilibrium allocations from studying the structural properties of thermodynamic equilibria. To be sure, these insights pertain to the formal structure of equilibrium solutions only, and they do not by themselves contain any substance content about thermodynamics or economics. For instance, based on what is known as the *Le Chatelier Principle* in thermodynamics (Kondepudi and Prigogine, 1998, pp. 239-240), Samuelson (1947) established the method of *comparative statics* in economics. This method explains the changes in the equilibrium solution of a constrained maximization problem (economic or thermodynamic) when one of the constraints is marginally tightened or relaxed. This has proved to be a very powerful tool and found widespread use in modern economics.

Yet, it seems as if the potential of exploiting the isomorphism of formal structures in thermodynamic and economic equilibria was fairly limited and is, by now, largely exhausted.

### 6.5.2 Analogies and Metaphors

A second approach takes thermodynamic concepts and transfers them into economic thinking as analogies and metaphors (Faber and Proops, 1985; Proops, 1985, 1987). For example, under this approach, 'order' and 'disorder' in an economy are interpreted as expressions of 'social entropy', or the economy is seen as a 'self-organizing dissipative system far from thermodynamic equilibrium'. Typically, no attempt is made under this approach to clearly define the various terms, such as 'order', 'entropy' or 'equilibrium', in either thermodynamic or economic terms. Instead, these terms are used to evoke certain associations with the reader.

To a reader who is well trained in both thermodynamics and economics, it remains unclear whether a term like e.g., 'equilibrium' refers to thermodynamic equilibrium (in the sense of a thermodynamic system being in a state of minimal thermodynamic potential, e.g., Helmholtz free energy) or to economic equilibrium (in the sense of an economy of households and firms being in a state of market equilibrium where demand equals supply). Certainly, using these terms in such a loose manner cannot have the status of making exact and deductive scientific statements about economic systems.

Despite these large unclarities, the analogies-and-metaphors-approach has merit as a heuristic, as it allows one to see economic phenomena in a new light. Thus, it generates new and potentially fruitful questions, rather than answering existing ones. In that sense, it is more a 'vision' in the sense of Schumpeter, than a rigorous analytical approach.

### 6.5.3 Energy, Entropy and Exergy Theories of Value

Some people argue that economic values based on subjective individual preferences are to some extent arbitrary and might be misleading in achieving sustainable solutions for environmental problems. In contrast, these people argue, sustainability requires the identification of the 'true' and 'objective' value of nature's goods and services, and of damages to these. Often, thermodynamic quantities are proposed to give such an 'objective' value rod, e.g., energy (Costanza, 1981; Hannon, 1973, 1979; Hannon et al., 1986; Odum, 1971), (low) entropy[13] or exergy (Bejan et al., 1996, p. 407).[14] In all of these cases, the argument is as follows. Energy (or alternatively exergy, low entropy) is the only really scarce factor here on Planet Earth. It measures the ultimate scarcity that we face in dealing with nature. Therefore, the amount of energy (exergy, low entropy) contained in every good or service measures its 'true' scarcity, and therefore should be taken as its value. Decisions concerning sustainability, so the argument, must be based on such energy/entropy/exergy-values, as they represent the ultimate scarcities.

From the economic point of view, this argument is untenable. It is untenable for the very same reasons why, for instance, a labour theory of value as advocated by David Ricardo or Karl Marx is untenable, and any other single-factor-theory of value would be untenable, be that factor energy, labour, oxygen, or whatever. 'Value', as it is understood in economics, results from the interplay of human goals and ends on the one hand (e.g., profit maximization, utility maximization or sustainability), and scarcity of means to achieve these ends on the other hand (e.g. natural resources, capital, labour, or time). The higher the goals and the scarcer the resources necessary to achieve them, the more valuable are these resources. There is an economic theorem which states that only under very limiting assumptions the value of a good or service is given by the total amount of a factor of production (e.g., energy or labour) which has been used, directly or indirectly, in producing it. This is the so-called non-substitution theorem, and it has been proven in 1951 independently by four real masterminds of economics: Arrow (1951), Koopmans (1951), Georgescu-Roegen (1951) and Samuelson (1951).[15] This theorem identifies the conditions, under which a single-factor-theory of value holds:

(A1) There is only one primary, i.e., non-producible, factor of production.
(A2) This factor is directly used in the production of every intermediate or final good or service.
(A3) All production processes are characterized by constant returns to scale; i.e., scaling the amounts of all inputs by a factor of $\lambda > 0$ also scales the amount of output produced by the same factor $\lambda$.
(A4) There is no joint production; i.e., every process of production yields exactly one output.

These are very restrictive assumptions. Only if (A1) – (A4) are fulfilled does a single-factor-theory of value fully explain the value of goods and services. If one of them does not hold, a single-factor-theory of value cannot provide a satisfactory explanation of value.

As for energy/entropy/exergy as a factor of production, one may safely assume that (A2) is fulfilled, and one may concede that (A1) can be taken to be fulfilled as well.[16] But in general, (A3) is not fulfilled, as many technologies are characterized by either increasing or decreasing returns to scale. Also, thermodynamic considerations, to which we will turn in detail later, imply that every process of production is joint production, such that (A4) is violated. This means, while energy, entropy or exergy theories of value are conceivable in very restricted models (characterized by conditions A1 – A4) they must be refuted for real ecological-economic systems. To be sure, while energy, entropy or exergy are important factors in explaining value, value is a complex and encompassing phenomenon, and thermodynamic quantities alone cannot provide a satisfactory explanation of value.

### 6.5.4 Thermodynamic Constraints on Economic Action

Another approach to integrating insights from thermodynamics into economics starts from the observation that the laws of thermodynamics constrain economic action. Thermodynamic laws specify what is possible and what is not possible in the transformation of energy and matter. Such transformations play an important role in any economy, for example in:

- The extraction of natural resources from the geo-bio-chemical-physical environment.
- The use of these resources in the production of goods and services.
- The generation and emission of wastes and environmental pollutants as by-products of desired goods.
- The recycling of wastes into secondary resources.

All of these transformations of energy and matter are at the center of interest in the field of ecological, environmental and resource economics. Hence, the laws of thermodynamics play an important role in describing relevant constraints and scarcities for the economic analysis of economy-environment interactions (Cleveland and Ruth, 1997).

This approach builds on a clear division of labour between the disciplines of thermodynamics and economics. The laws of thermodynamics are being used to capture the constraints on transformations of energy and matter. Their role is limited to this particular task. Based on this conceptualization of constraints, methods and concepts from economics are then being used to study allocations in an economy which result from the optimizing behavior of firms and households; e.g., profit-maximizing resource extraction and production firms as well as utility-maximizing households purchasing the consumer goods so produced.

This approach can directly be operationalized, and it is empirically meaningful for ecological economics. It lends itself quite naturally to modelling. One can distinguish between different model types for integrated thermodynamic-economic analysis, according to which thermodynamic concepts and laws they incorporate:

- Models incorporating mass and the conservation of mass (First Law), either for one particular material (say, copper) or for a number of materials.

- Models incorporating energy and conservation of energy (First Law), sometimes in variants such as emergy (‘embodied energy’).
- Models incorporating entropy and entropy generation (Second Law).
- Models incorporating energy and entropy, sometimes in the form of exergy (First and Second Law).
- Models incorporating mass, energy and entropy (First and Second Law).

Models based on the First Law are useful to study the economic implications from the scarcities due to physical conservation of mass and energy in the throughflow of materials and energy through the economy. Models based on the Second Law are useful to study the economic implications from the scarcities due to the temporal directedness of this throughflow and its quailtative degradation by dissipation of energy and dispersal of matter.

## 6.6 IMPLICATIONS OF AND INSIGHTS FROM THERMODYNAMIC MODELS

The use of thermodynamic concepts, laws and models in ecological economics is an ongoing endeavour. So far, it has revealed a number of relevant implications and insights about different aspects of economy-environment interactions.[17]

### 6.6.1 Materials Balance: The ‘Planet Earth’ Perspective

The Materials Balance Principle is based on the Law of Conservation of Mass as implied by the First Law of Thermodynamics (Boulding, 1966; Ayres and Kneese, 1969; Kneese et al., 1972, Ayres 1978).[18] Since mass cannot be created, but is conserved in all transformations, all material resource inputs that enter a production process (i) diminish the corresponding resource reservoir, and (ii) eventually become waste.

This principle has lead to viewing the Earth, including the human society, as a ‘spaceship’ (Boulding, 1966), which is completely closed to the surrounding space in material terms. Thus, all material transformations on Earth should be managed in a self-reliant and sustainable way.

### 6.6.2 Irreversibility of (Micro- and Macro-) Economic Processes

All processes of macroscopic change are irreversible. Examples include natural processes, such as the growing and blooming of a flower, as well as technical processes, such as the burning of fossil fuels in combustion engines. The entropy concept and the Second Law of Thermodynamics have been coined such as to capture this fact of nature (Kondepudi and Prigogine, 1998; Zeh, 2001).

The relevance of thermodynamic irreversibility for economics lies in the fact that it precludes the existence of perpetual motion machines, i.e., devices which use a limited reservoir of available energy to perform work forever. It is an everyday experience that there exists no such thing as a perpetual motion machine. This holds for the micro-level, i.e. individual production processes, as well as for the macro-level, i.e. the economy at large (Georgescu-Roegen, 1971).

In order to make this insight accessible to economic analysis it is necessary to adequately represent thermodynamic irreversibility as a constraint for economic action. Modern economic theory has devoted some effort to incorporating irreversibility into production theory. However, the standard irrversibility concept of economics, which is due to Arrow and Debreu (1954) and Debreu (1959), does not encompass thermodynamic irreversibility; it only establishes temporal irreversibility – a weaker form of irreversibility (Baumgärtner, 2000b).

### 6.6.3 Resource Extraction and Waste Generation

The insights described in Sections 6.6.1 and 6.6.2 have been applied, in particular, to the analysis of mineral resource extraction (e.g., Ruth 1995a, 1995b, 1995c), the generation of wastes and pollution (Kümmel, 1989; Kümmel and Schüssler, 1991), and the relation between the two (Faber, 1985; Faber et al., [1983]1995). At a very abstract level, high entropy (or exergy lost) is the ultimate form of waste (Kümmel, 1989; Kümmel and Schüssler, 1991; Ayres and Martinás, 1995; Ayres et al., 1998).

### 6.6.4 Representation of the Production Process

Every process of production is, at root, a transformation of energy and matter (Ayres and Kneese, 1969). Hence, the laws of thermodynamics provide a suitable analytical framework for rigorously deducing insights into the physical aspects of production (Baumgärtner 2000a). In particular, any representation of production in economic models should be in accordance with the laws of thermodynamics. Therefore, the neoclassical production function, which is the standard way of representing the production process in economic models, has been critically discussed against the background of thermodynamics. It has become apparent that this concept is incompatible with the laws of thermodynamics for a number of reasons:

(i) Georgescu-Roegen (1971) claims that the neoclassical production function is incompatible with the laws of thermodynamics, basically because it does not properly reflect the irreversible nature of transformations of energy and matter, and because it confounds flow and fund quantities (Daly, 1997b; Kurz and Salvadori, 2003).

(ii) One essential factor of production, which is very often omitted from the explicit representation, is energy (actually: exergy) (Kümmel, 1989; Ayres, 1998).[19] Its exact role for the production process, and its interplay with other production factors, such as capital or material resources, studied in engineering thermodynamics (e.g. Bejan, 1996, 1997; Bejan et al., 1996; see also Sec. 6.6.5 below).

(iii) The conservation laws for energy and matter imply that there are limits to substitution between energy-matter inputs, which are subject to the laws of thermodynamics, and other inputs such as labour or capital, which lie outside the domain of thermodynamics (Berry and Andresen, 1982; Berry et al., 1978; Dasgupta and Heal, 1979, Chap. 7).

(iv) From the First and Second Laws of Thermodynamics it becomes obvious that '[g]iven the entropic nature of the economic process, waste is an output just as unavoidable as the input of natural resources' (Georgescu-Roegen 1975, p. 357). This holds not only for the economy at large, but for every individual process of production at the micro-level (Faber et al., 1998; Baumgärtner 2000a, Chapter 5, 2002; Baumgärtner and de Swaan Arons, 2003). As a consequence, there is no such thing as 'single production'; i.e., the production of just one single output as modelled by the neoclassical production function. Rather, all production is joint production, i.e. there is necessarily more than one output (Faber et al., 1998; Baumgärtner et al., 2001).

All of these apparent inconsistencies between the laws of thermodynamics and the standard assumptions about the neoclassical production function have led to more general descriptions of the production process, which blend the traditional theory of production with thermodynamic principles (Anderson, 1987; Baumgärtner, 2000a, Chap. 4; Pethig, 2003, Sec. 3.3).

### 6.6.5 Finite-Time/Finite-Size Thermodynamics: Exergy-Engineering

Recent research in the applied field of engineering thermodynamics has addressed the circumstance that chemical and physical processes in industry never happen in a completely reversible way between one equilibrium state and another equilibrium state. Rather, these processes are enforced by the operator of the process and they are constrained in space and time. This has led to an extension of ideal equilibrium thermodynamics, known under the name of *finite-time/finite-size thermodynamics* (e.g. Andresen et al., 1984; Bejan, 1996, 1997; Bejan et al., 1996).

From the point of view of finite-time/finite-size thermodynamics it becomes obvious that the minimum exergy requirement and minimum waste production in chemical or physical processes is considerably higher than that suggested by ideal equilibrium thermodynamics. The reason for the increased exergy requirement (which entails an increased amount of waste at the end of the process) lies in the fact that chemical and physical transformations are forced to happen over a finite time by the operator of the production plant, which necessarily causes some dissipation of energy.

The finite-time/finite-size consideration is a very relevant consideration for many production processes, in particular in the chemical industry. Finite-time/finite-size thermodynamics allows one to exactly identify, trace down and quantify exergetic inefficiencies at the individual steps of a production processes (Bejan, 1996, 1997; Bejan et al., 1996; Brodyansky et al., 1994; Creyts, 2000; Szargut et al., 1988), along the entire chain of a production process (Ayres et al., 1998; Cornelissen and Hirs, 1999; Cornelissen et al., 2000), for whole industries (Dewulf et al., 2000; Hinderink et al., 1999; Ozdogan and Arikol, 1981), and for entire national economies (Nakićenović et al., 1996; Schaeffer and Wirtshafter, 1992; Wall, 1987, 1990; Wall et al., 1994). Thus, it yields valuable insights in the origins of exergy losses and forms a tool for designing industrial production systems in an efficient and sustainable manner (Connelly and Koshland, 2001; de Swaan Arons and van der Kooi, 2001).

Furthermore, it becomes apparent that energy/exergy and time are substitutes as factors of production in many production processes (Andresen et al., 1984; Berry and Andresen, 1982; Spreng, 1993). A production process may be speeded up at the expense of employing more energy/exergy, and the use of energy/exergy may be reduced by allowing the production process to just take longer. Prominent examples for such a trade-off-relationship are transport services or chemical reaction processes.

### 6.6.6 Thermodynamic and Economic Efficiency

Both thermodynamics and economics analyse systems in terms of their ‘efficiency’. Both concepts may be applied to the very same system; e.g., a production plant or a whole national economy. Yet, the thermodynamic and the economic notions of efficiency fundamentally differ, as they refer to very different variables of the system. In fact, the two notions are completely independent (Berry et al., 1978; Dasgupta and Heal, 1979, Chap. 7; Baumgärtner, 2001). As a consequence, thermodynamic efficiency is neither necessary nor sufficient for economic efficiency, even when economic efficiency includes concerns for energy, resources and environmental quality.

### 6.6.7 Sustainability: Limits to Economic Growth

From the very beginning, the recourse to thermodynamic arguments in ecological economics was motivated by a long-term and global concern for the sustainable existence of humans on 'Planet Earth' (Boulding, 1966; Georgescu-Roegen, 1971; Daly 1973, [1977]1991). The pre-analytic vision behind this concern was that of the human economy as an open subsystem of the larger, but finite, closed, and non-growing system of the biogeophysical environment.

In that view, thermodynamic analysis has helped to sketch the potential and limits of economic growth. It has turned out that there exist limits to the growth of energy-matter throughput through the economy, which may ultimately set limits to economic growth. This claim is vindicated by the following arguments:[20]

(i) Conservation of mass implies that the marginal product as well as the average product of a material resource input may be bounded from above (Baumgärtner, 2003b). This means that the usual Inada conditions (Inada, 1963) do not hold for material resource inputs. This is important since the Inada conditions are usually held to be crucial for establishing steady state growth under scarce exhaustible resources (e.g. Dasgupta and Heal, 1974; Solow, 1974; Stiglitz, 1974).

(ii) As described in Section 6.6.4 above, the conservation laws for energy and matter imply that there are limits to substitution between energy-matter inputs, which are subject to the laws of thermodynamics, and other inputs such as labour or capital, which lie outside the domain of thermodynamics (Berry and Andresen, 1982; Berry et al., 1978; Dasgupta and Heal, 1979, Chap. 7). This is important since substitutability among essential and scarce production factors (with an elasticity of substitution not smaller than one) is usually held to be crucial for establishing steady state growth (e.g. Dasgupta and Heal, 1974; Solow, 1974; Stiglitz, 1974).

(iii) Some have posited that resource scarcity can be overcome by recycling. However, thermodynamic analysis clearly shows that there are limits to recycling as well (Ayres, 1999; Craig, 2001).

(iv) Others have posited that technical progress is an important driver of economic growth, and that technical progress will continue. However, thermodynamic analysis clearly shows that there are limits to technical progress (Ruth, 1995a, b, c).

## 6.7 CONCLUSION AND CAVEAT: THERMODYNAMICS AND SUSTAINABILITY

Taken together, thermodynamic concepts, laws and models are relevant for ecological economics in various ways and on different levels of abstraction.

(i) As all processes of change are, at bottom, processes of energy and material transformation the concepts and laws of thermodynamics apply to all of them. The framework of thermodynamics thus creates a unifying perspective on ecology, the physical environment, and the economy. This unifying framework, combined with economic and ecological analysis, allows asking questions that would not have been asked from the perspective of one scientific discipline alone.

(ii) On a more specific level, thermodynamic concepts allow the incorporation of physical driving forces and constraints into models of economy-environment interactions, both microeconomic and macroeconomic. They are essential for understanding to what extent resource and energy scarcity, nature's capacity to assimilate human wastes and pollutants, as well as the irreversibility of transformation processes, constrain economic action. Thermodynamic concepts thus allow economics to relate to its biogeophysical basis, and yield insights about that relationship which are not available otherwise.

(iii) On an even more applied level, thermodynamic concepts provide tools of quantitative analysis of energetic and material transformations for engineers and managers. They may be used to design industrial production plants or individual components of those such as to maximize their energetic efficiency, and to minimize their environmental impact.

With its rigorous but multifarious character as a method of analysis, its rich set of fruitful applications, and its obvious potential to establish relations between the natural world and purposeful human action, thermodynamics is one of the cornerstones in the conceptual foundation of ecological economics.

However, one important caveat seems to be in place. Thermodynamics is a purely descriptive science. That means, it only allows one to make statements of the kind 'If A, then B'. In particular, it is not a normative science. By itself, it neither includes nor allows value statements (Baumgärtner, 2000a, pp. 65-66) or statements of the kind 'C is a good, and therefore desirable, state of the world, but D is not'.[21] In contrast, sustainability is essentially a normative issue (Faber et al., 1995; Faber et al., 1996, Chap. 5). Sustainability is about the question 'In what kind of world do we want to live today and in the future?', thus, inherently including a dimension of desirability. A purely descriptive science alone, like thermodynamics, cannot give an answer to that question.

Thermodynamics, however, is necessary to identify clearly the feasible options of development and their various properties, before a choice is then made about which option to choose based on some normative criteria. That choice requires a valuation or, more generally, a normative judgment of the different options at hand. It is therefore necessary not only to know the energetic and material basis of society's metabolism – both current and feasible alternatives – but also to link these thermodynamic aspects to the human perception and valuation of natural resources, commodity products and waste joint products, and the state of the natural environment.

The role of thermodynamics for conceiving sustainable modes of societal metabolism, therefore, is relative but essential. Thermodynamics is necessary to identify which options and scenarios of resource use, economic production, and waste generation are feasible and which are not. It, thereby, contributes to making informed choices about the future.

## NOTES

1 In particular, in the late 1960s and early 1970s economists discovered the relevance of thermodynamics for environmental and resource economics. Pethig (2003), Spash (1999, p. 418) and Turner (1999, Section 2) describe this development in detail.
2 The works of Georgescu-Roegen are surveyed in a number of recent volumes (e.g. Beard and Lozada, 1999; Mayumi, 2001; Mayumi and Goody, 1999) and a special edition of the journal *Ecological Economics* (Vol. 22, No. 3, 1997).
3 See Baumgärtner et al. (1996) for a summary of that discussion.
4 Georgescu-Roegen posited that in a closed system, matter is distributed in a more and more disordered way. He called this claim 'Fourth Law', in extension of the well established three laws of classical thermodynamics (see Section 6.4).
5 Later, this system was extended to also include savings and investment, as well as imports and exports.
6 Schumpeter (1954, p. 42) defines a *vision* as the 'preanalytic cognitive act that necessarily precedes any scientific analysis'.
7 For an overview see e.g. Freeman (1993) or Hanley and Spash (1993).
8 Section 6.3 is taken from Baumgärtner (2002, Sec. 2.3). For a comprehensive introduction to (phenomenological) thermodynamics see Callen (1985), Kondepudi and Prigogine

(1998) or Zemansky and Dittman (1997).

9 Note that this does not mean that the initial state of the system can never be restored. However, in order to restore the system's initial state, the initially isolated system has to be opened to the influx of energy. For instance, the initial state could be restored by removing the system's insulation and performing work on the system from the outside, e.g. by pressing all the molecules into the left part with a mobile wall that is initially at the right hand end of the system and from there on moves left.

10 Balian (1991), Huang (1987) and Landau and Lifshitz (1980) give an introduction to statistical mechanics.

11 Exergy values for many materials are typically calculated for an environmental temperature of 298.15 K and pressure of 101.325 kPa and can be found in tables, such as e.g. in Szargut et al. (1988, Appendix).

12 Söllner (1997) distinguishes between three approaches. He does not take into account the formal-isomorphism-approach.

13 Burness et al. (1980, p. 7) and Patterson (1998) claim that Georgescu-Roegen (1971, Chap. 5) proposes a (low) entropy theory of value. This claim is wrong. On the contrary, Georgescu-Roegen (1971, p. 282) explicitly warns against such an interpretation. Note that Georgescu-Roegen (1979) also gives an explicit rebuttal of energy theories of value. See Baumgärtner et al. (1996, pp. 123-125) for details.

14 Patterson (1998) surveys different theories of value in ecological economics.

15 Note that three of these – Arrow, Koopmans, and Samuelson – have been awarded the Nobel Prize in Economics later on. (Some claim that the fourth one – Georgescu-Roegen – would have deserved it as well.)

16 One may as well consider space and time as primary production factors, as they surely enter every process of production in some sense. But then, energy is not the only primary factor any more.

17 Surveys of this area of research include Baumgärtner et al. (1996), Beard and Lozada (1999), Burley and Foster (1994), Daly (1997a), Mayumi and Gowdy (1999), Pethig (2003) and Ruth (1999).

18 Pethig (2003) surveys the Materials-Balance-Principle's origin and impact for environmental and resource economics.

19 Eonometric studies show that the production factor energy (exergy) explains an unexpectedly large share of economic growth observed over the 20$^{th}$ century in the US, German or Japanese economies (Kümmel et al., 1985, 2000; Ayres et al., 2003).

20 Cleveland and Ruth (1997) present these arguments in more detail and review the relevant literature.

21 This holds even for the notion of *thermodynamic efficiency*, which is a purely technical notion (see the discussion in Section 6.6.6 above).

## REFERENCES

Anderson, C.L. (1987), 'The production process: inputs and wastes', *Journal of Environmental Economics and Management*, **14**, 1-12.

Andresen, B., P. Salomon and R.S. Berry (1984), 'Thermodynamics in finite time', *Physics today*, **37**(9), 62-70.

Arrow, K.J. (1951), 'Alternative proof of the substitution theorem for Leontief models in the general case', in T.C. Koopmans (ed.), *Activity Analysis of Production and Allocation*, New York: Wiley, pp. 155-164.

Arrow, K.H. and G. Debreu (1954), 'Existence of an equilibrium for a competitive economy', *Econometrica*, **22**, 265-290.

Ayres, R.U. (1978), *Resources, Environment and Economics – Applications of the Materials/Energy Balance Principle*, New York: Wiley.

Ayres, R.U. (1998), 'Eco-thermodynamics: economics and the second law', *Ecological Economics*, **26**, 189-209.
Ayres, R.U. (1999), 'The second law, the fourth law, recycling, and limits to growth', *Ecological Economics*, **29**, 473-483.
Ayres, R.U., L.W. Ayres and K. Martinás (1998), 'Exergy, waste accounting, and life-cycle analysis', *Energy*, **23**, 355-363.
Ayres, R.U., L.W. Ayres and B. Warr (2003), 'Exergy, power and work in the US economy 1900-1998', *Energy – The International Journal*, **28**, 219-273.
Ayres, R.U. and A.V. Kneese (1969), 'Production, consumption, and externalities', *American Economic Review*, **59**, 282-297.
Ayres, R.U. and K. Martinás (1995), 'Waste potential entropy: the ultimate ecotoxic?', *Economie Appliquée*, **48**, 95-120.
Balian, R. (1991), *From Microphysics to Macrophysics, Vol. I,* Heidelberg: Springer.
Baumgärtner, S. (2000a), *Ambivalent Joint Production and the Natural Environment. An Economic and Thermodynamic Analysis*, Heidelberg: Physica Verlag.
Baumgärtner, S. (2000b), 'Different notions of irreversibility in production', *Discussion Paper No. 337*, Department of Economics, University of Heidelberg, November 2000.
Baumgärtner, S. (2001), 'Thermodynamic and economic notions of efficiency', Contribution to the Symposium *Sustainable Processes and Products*, 30 May 2001, Delft University of Technology, Department of ChemTech.
Baumgärtner, S. (2002), 'Thermodynamics of waste generation', in K. Bisson and J. Proops (eds), *Waste in Ecological Economics*, Cheltenham: Edward Elgar, pp. 13-37.
Baumgärtner, S. (2003a), 'Entropy', in International Society for Ecological Economics (ed.), *Online Encyclopedia of Ecological Economics* (http://www.ecoeco.org/publica/encyc.htm).
Baumgärtner, S. (2003b), 'The Inada conditions for material resource inputs reconsidered', *Discussion Paper No. 396*, Department of Economics, University of Heidelberg.
Baumgärtner, S., H. Dyckhoff, M. Faber, J. Proops and J. Schiller (2001), 'The concept of joint production and ecological economics', *Ecological Economics*, **36**, 365-372.
Baumgärtner, S., M. Faber and J. Proops (1996), 'The use of the entropy concept in Ecological Economics', in Faber, M., R. Manstetten and J.Proops (1996), pp. 115-135.
Baumgärtner, S. and J. de Swaan Arons (2003), 'Necessity and inefficiency in the generation of waste: a thermodynamic analysis', *Journal of Industrial Eco logy*, **7**, 113-124.
Beard, T.R. and G.A. Lozada (1999), *Economics, Entropy and the Environment. The Extraordinary Economics of Nicholas Georgescu-Roegen*, Cheltenham: Edward Elgar.
Bejan, A. (1996), *Entropy Generation Minimization*, Boca Raton: CRC Press.
Bejan, A. (1997), *Advanced Engineering Thermodynamics*, 2nd ed., New York: Wiley.
Bejan, A., G. Tsatsaronis and M. Moran (1996), *Thermal Design and Optimization*, New York: Wiley.

Berry, R.S. and B. Andresen (1982), 'Thermodynamic constraints in economic analysis', in W.C. Schieve and P. Allen (eds), *Self-Organization and Dissipative Structures. Applications in the Physical and Social Sciences*, Austin: University of Texas Press, pp. 323-338.

Berry, R.S., P. Salamon and G.M. Heal (1978), 'On a relation between economic and thermodynamic optima', *Resources and Energy*, **1**, 125-137.

Boltzmann, L. (1877), 'Über die Beziehung eines allgemeinen mechanischen Satzes zum zweiten Hauptsatz der Wärmetheorie', *Sitzungsberichte der Kaiserlichen Akademie der Wissenschaften in Wien, Abt. 2*, **75**, 67-73.

Boulding, K.E. (1966), 'The economics of the coming spaceship Earth', in H. Jarrett (ed.), *Environmental Quality in a Growing Economy*, Baltimore: Johns Hopkins University Press, pp. 3-14.

Brodyansky, V.M., M.V. Sorin and P. Le Goff (eds) (1994), *The efficiency of Industrial processes: exergy analysis and optimization,* Amsterdam: Elsevier.

Brown, L.R. (2001), *Eco-Economy. Building an Economy for the Earth*. New York: W.W. Norton.

Burley, P. and J. Foster (eds) (1994), *Economics and Thermodynamics: New Perspectives on Economic Analysis*. Dordrecht: Kluwer.

Burness, H.S., R.G. Cummings, G. Morris and I. Paik (1980), 'Thermodynamic and economic concepts as related to resource-use policies', *Land Economics*, **56**, 1-9.

Callen, H.B. (1985), *Thermodynamics and an Introduction to Thermostatics*, 2nd edn., New York: Wiley.

Clausius, R. (1854), *Fortschritte der Physik*, **10**.

Clausius, R. (1865), 'Über verschiedene für die Anwendung bequeme Formen der Hauptgleichungen der mechanischen Wärmetheorie', *Annalen der Physik*, **125**, 353-400.

Cleveland, C.J. and M. Ruth (1997), 'When, where and by how much does thermodynamics constrain economic processes? A survey of Nicholas Georgescu-Roegen's contribution to ecological economics' *Ecological Economics*, **22**, 203-223.

Connelly, L. and K.P. Koshland (2001), 'Exergy and industrial ecology', *Exergy,* **1**, 146-165 and 234-255.

Cornelissen, R.L. and G.G. Hirs (1999), 'Exergy analysis in the process industry', in A. Bejan and E. Mamut (eds), *Thermodynamic Optimization of Complex Energy systems*, Dordrecht: Kluwer Academic Publishers.

Cornelissen, R.L., P.A. Nimwegen, and G.G. Hirs (2000), 'Exergetic Life-cycle Analysis', in *Proceedings of ECOS 2000*, Enschede.

Costanza, R. (1981), 'Embodied energy, energy analysis, and economics', in H.E. Daly (ed.), *Energy, Economics, and the Environment*, Boulder: Westview Press.

Craig, P.P. (2001), 'Energy limits to recycling', *Ecological Economics*, **36**, 373-84.

Creyts, J.C. (2000), *Use of extended exergy analysis as a tool to optimize the environmental performance of industrial processes*, Ph.D. Thesis, Berkeley: University of California, Department of Mechanical Engineering.

Daly, H.E. (1973), *Toward a Steady-State Economy*, San Francisco: W.H. Freeman.

Daly, H.E. ([1977]1991), *Steady State Economics. The Economics of Biophysical Equilibrium and Moral Growth*, 2nd edn, San Francisco: W.H. Freeman.

Daly, H.E. (1992), 'Is the entropy law relevant to the economics of natural resources? Yes, of course it is!', *Journal of Environmental Economics and Management*, **23**, 91-95.

Daly, H.E. (ed.) (1997a), *The Contribution of Nicholas Georgescu Roegen*, Special issue of *Ecological Economics*, **22** (3).

Daly, H.E. (1997b), 'Georgescu-Roegen versus Solow/Stiglitz' *Ecological Economics*, **22**, 261-266.

Dasgupta, P. and G. Heal (1974), 'The optimal depletion of exhaustible resources', *Review of Economic Studies*, **41** (Symposium on the Economics of Exhaustible Resources), 3-28.

Dasgupta, P.S. and G.M. Heal (1979), *Economic Theory and Exhaustible Resources*, Cambridge: Cambridge University Press.

Debreu, G. (1959), *Theory of Value – An Axiomatic Study of Economic Equilibrium*, New York: Wiley.

de Swaan Arons, J. and H.J. van der Kooi (2001), 'Towards a metabolic society: a thermodynamic view', *Green Chemistry*, **3**(4), G53-G55.

Dewulf, J., J.M. Mulder, M.M.D. van den Berg, H. Van Langenhove, H.J. van der Kooi and J. de Swaan Arons (2000), 'Illustrations towards quantifying the sustainability of technology', *Green Chemistry*, **2**(3), 108-114.

Faber, M. (1985), 'A biophysical approach to the economy: entropy, environment and resources', in W. van Gool and J.J.C. Bruggink (eds), *Energy and Time in the Economic and Physical Sciences*, Amsterdam: North Holland, pp. 315-335.

Faber, M., F. Jöst and R. Manstetten (1995), 'Limits and perspectives on the concept of sustainable development', *Economie Appliquée*, **48**, 233-251.

Faber, M., R. Manstetten and J. Proops (1996), *Ecological Economics – Concepts and Methods,* Cheltenham: Edward Elgar.

Faber, M., H. Niemes and G. Stephan ([1983]1995), *Entropy, Environment and Resources: An Essay in Physico-Economics,* 2nd edn, Heidelberg: Springer.

Faber, M. and J. Proops (1985), 'Interdisciplinary research between economists and physical scientists: retrospect and prospect', *Kyklos*, **38**, 599-616.

Faber, M. and J. Proops (1990), *Evolution, Time, Production and the Environment*, Heidelberg: Springer.

Faber, M., J. Proops and S. Baumgärtner (1998), 'All production is joint production – a thermodynamic analysis', in S. Faucheux, J. Gowdy and I. Nicolaï (eds), *Sustainability and Firms. Technological Change and the Changing Regulatory Environment*, Cheltenham: Edward Elgar, pp. 131-158.

Falk, G. and W. Ruppel (1976), *Energie und Entropie. Eine Einführung in die Thermodynamik*, Heidelberg: Springer.

Freeman, A.M. (1993), *The Measurement of Environmental and Resource Values: Theory and MEasurement*, Washington, D.C.: Resources for the Future.

Georgescu-Roegen, N. (1951), 'Some properties of a generalized Leontief model', in T.C. Koopmans (ed.), *Activity Analysis of Production and Allocation*, New York: Wiley, pp. 165-73.

Georgescu-Roegen, N. (1971), *The Entropy Law and the Economic Process*, Cambridge/MA: Harvard University Press.

Georgescu-Roegen, N. (1975), 'Energy and economic myths', *Southern Economic Journal*, **41**, 347-81.

Georgescu-Roegen, N. (1979), 'Energy analysis and economic valuation', *Southern Economic Journal*, **45**, 1023-1058.

Gray, L.C. (1913), 'The economic possibilities of conservation', *Quarterly Journal of Economics*, **27**, 497-519.

Gray, L.C. (1914), 'Rent under the assumption of exhaustibility', *Quarterly Journal of Economics*, **28**, 466-489.

Hanley, N. and C.L. Spash (1993), *Cost-Benefit Analysis and the Environment*, Aldershot, UK: Edward Elgar.

Hannon, B. (1973), 'An energy standard of value', *American Acadamey of Political Science Annual*, **410**, 139-153.

Hannon, B. (1979), 'Total energy cost in ecosystems', *Journal of Theoretical Biology*, **56**: 279-293.

Hannon, B., R. Costanza and R.A. Herendeen (1986), 'Measures of energy cost and value in ecosystems', *Journal of Environmental Economics and Management*, **13**, 391-401.

Hinderink, P., H.J. van der Kooi and J. de Swaan Arons (1999), 'On the efficiency and sustainability of the process industry', *Green Chemistry*, **1**(6), G176-G180.

Hotelling, H. (1931), 'The economics of exhaustible resources', *Journal of Political Economy*, **39**, 137-175.

Huang, K. (1987), *Statistical Mechanics*, 2nd ed., New York: Wiley.

Inada, K.I. (1963), 'On a two-sector-model of economic growth: comments and a generalization', *Review of Economic Studies*, **30**, 119-127.

Kåberger, T. and Månsson, B. (2001), 'Entropy and economic processes – physics perspectives', *Ecological Economics*, **36**, 165-179.

Khalil, E.L. (1990), 'Entropy law and exhaustion of natural resources: Is Nicholas Georgescu-Roegen's paradigm defensible?', *Ecological Economics*, **2**, 163-178.

Kneese, A.V., R.U. Ayres and R.C. d'Arge (1972), *Economics and the Environment: A Materials Balance Approach*, Washington: Resources for the Future.

Kondepudi, D. and I. Prigogine (1998), *Modern Thermodynamics. From Heat Engines to Dissipative Structures*, New York: Wiley.

Koopmans, T.C. (1951), 'Alternative proof of the substitution theorem for Leontief models in the case of three industries', in T.C. Koopmans (ed.), *Activity Analysis of Production and Allocation*, New York: Wiley, pp. 147-154.

Kümmel, R. (1989), 'Energy as a factor of production and entropy as a pollutian indicator in macroeconomic modelling', *Ecological Economics*, **1**, 161-180.

Kümmel, R., D. Lindenberger and W. Eichhorn (2000), ‚The productive power of energy and economic evolution', *Indian Journal of Applied Economics*, **8**, 231-262.

Kümmel, R. and U. Schüssler (1991), 'Heat equivalents of noxious substances: a pollution indicator for environmental accounting', *Ecological Economics*, **3**, 139-156.

Kümmel, R., W. Strassl, A. Grosser and W. Eichhorn (1985), ‚Technical progress and energy dependent production functions', *Journal of Economics*, **45**, 285-311.

Kurz, H.D. and N. Salvadori (2003), 'Fund-flow versus flow-flow in production theory: Reflections on Georgescu-Roegen's contribution', *Journal of Economic Behavior and Organization*, **51**, 487-505.

Landau, L.D. and E.E. Lifshitz (1980), *Statistical Physics*, 3rd ed., Oxford: Pergamon.

Lozada, G.A. (1991), 'A defense of Nicholas Georgescu-Roegens's paradigm', *Ecological Economics*, **3**, 157- 160.

Lozada, G.A. (1995), 'Georgescu-Roegens's defence of classical thermodynamics revisited', *Ecological Economics*, **14**, 31-44.

Mayumi, K. (2001), *The Origins of Ecological Economics. The Bioeconomics of Georgescu-Roegen*, London: Routledge.

Mayumi, K. and J.M. Gowdy (eds) (1999), *Bioeconomics and Sustainability. Essays in Honor of Nicholas Georgescu-Roegen*, Cheltenham: Edward Elgar.

Nakićenović, N., P.V. Gilli and R. Kurz (1996), 'Regional and global exergy and energy efficiencies', *Energy*, **21**, 223-237.

Norgaard, R.B. (1986), ‘Thermodynamic and economic concepts as related to resource-use policies: synthesis’, *Land Economics*, **62**, 325-328.
Odum, H.T. (1971), *Environment, Power and Society*, New York: Wiley.
Ozdogan, S. and M. Arikol (1981), ‘Energy and exergy analysis of selected Turkish industries’, *Energy*, **18**, 73-80.
Patterson, M.G. (1998), ‘Commensuration and theories of value in ecological economics’, *Ecological Economics*, **25**, 105-125.
Perrings, C. (1987), *Economy and Environment: A Theoretical Essay on the Interdependence of Economic and Environmental Systems*, Cambridge: Cambridge University Press.
Pethig, R. (2003), ‘The “materials balance approach” to pollution: its origin, implications and acceptance’, *Discussion Paper 105-03*, University of Siegen.
Pigou, A.C. (1912), *Wealth and Welfare*, London: Macmillan.
Pigou, A.C. (1920), *The Economics of Welfare*, London: Macmillan.
Prigogine, I. (1962), *Introduction to Non-Equilibrium Thermodynamics*, New York: Wiley.
Prigogine, I. (1967), *Thermodynamics of Irreversible Processes*, New York: Interscience.
Proops, J. (1985), ‘Thermodynamics and economics: from analogy to physical functioning’, in van W. van Gool and J.J.C. Bruggink (eds), *Energy and Time in the Economic and Physical Sciences*, Amsterdam: North-Holland.
Proops, J. (1987), ‘Entropy, information and confusion in the social sciences’, *Journal of Interdisciplinary Economics*, **1**, 224-242.
Ruth, M. (1993), *Integrating Economics, Ecology and Thermodynamics*, Dordrecht: Kluwer.
Ruth, M. (1995a), ‘Technology change in the US iron and steel production’, *Resources Policy*, **21**, 199-214.
Ruth, M. (1995b), ‘Thermodynamic constraints on optimal depletion of copper and aluminum in the United States: A dynamic model of substitution and technical change’, *Ecological Economics*, **15**, 197-213.
Ruth, M. (1995c), ‘Thermodynamic implications for natural resource extraction and technical change in U.S. copper mining’, *Environmental and Resource Economics*, **6**, 187-206.
Ruth, M. (1999), ‘Physical principles in environmental economic analysis’, in J.C.J.M. van den Bergh (ed.), *Handbook of Environmental and Resource Economics*, Cheltenham: Edward Elgar, pp. 855-866.
Samuelson, P.A. (1947), *Foundations of Economic Analysis*, Cambridge, MA: Harvard University Press.
Samuelson, P.A. (1951), ‘Abstract of a theorem concerning substitutability in open Leontief models’, in T.C. Koopmans (ed.), *Activity Analysis of Production and Allocation*, New York: Wiley, pp. 142-146.
Schaeffer, R. and R.M. Wirtshafter (1992), ‘An exergy analysis of the Brazilian economy: from energy products to final use’, *Energy*, **17**, 841-855.
Schumpeter, J.A. (1954), *History of Economic Analysis*, London: Oxford University Press.
Söllner, F. (1997), ‘A reexamination of the role of thermodynamics for environmental economics’, *Ecological Economics*, **22**, 175-201.
Solow, R.M. (1974), ‘Intergenerational equity and exhaustible resources’, *Review of Economic Studies*, **41** (Symposium on the Economics of Exhaustible Resources), 29-45.

Spash, C. (1999), 'The development of environmental thinking in economics', *Environmental Values*, **8**, 413-435.
Spreng, D. (1993), 'Possibilities for substitution between energy, time and information', *Energy Policy*, **21**, 13-23.
Stiglitz, J. (1974), 'Growth with exhaustible natural resources: Efficient and optimal growth paths', *Review of Economic Studies*, **41** (Symposium on the Economics of Exhaustible Resources), 123-152.
Szargut, J., D.R. Morris and F.R. Steward (1988), *Exergy Analysis of Thermal, Chemical, and Metallurgical Processes*, New York: Hemisphere Publishing.
Townsend, K.N. (1992), 'Is the entropy law relevant to the economics of natural resource scarcity? Comment', *Journal of Environmental Economics and Management*, **23**, 96-100.
Turner, R.K. (1999), 'Environmental and ecological economics perspectives', in J.C.J.M. van den Bergh (ed.), *Handbook of Environmental and Resource Economics*, Cheltenham: Edward Elgar, pp. 1001-1033.
Wall, G. (1987), 'Exergy conversion in the Swedish society', *Resources and Energy*, **9**, 55-73.
Wall, G. (1990), 'Exergy conversion in the Japanese society', *Energy*, **15**, 435-444.
Wall, G., E. Sciubba and V. Naso (1994), 'Exergy use in the Italian society', *Energy*, **19**, 1267-1274.
Williamson, A.G. (1993), 'The second law of thermodynamics and the economic process', *Ecological Economics*, **7**, 69-71.
Young, J.T. (1991), 'Is the entropy law relevant to the economics of natural resource scarcity?', *Journal of Environmental Economics and Management*, **21**, 169-179.
Young, J.T. (1994), 'Entropy and natural resource scarcity: a reply to the critics', *Journal of Environmental Economics and Management*, **26**, 210-213.
Zeh, H.D. (2001), *The Physical Basis of the Direction of Time*, $4^{th}$ edn, Berlin: Springer.
Zemansky, M.W. and R.H. Dittman (1997), *Heat and Thermodynamics: An Intermediate Textbook*, $7^{th}$ ed., New York: McGraw-Hill.