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Bulletin of Science Technology Society 2008; 28; 260
DOI: 10.1177/0270467608316097

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Sustaining Action and Optimizing Entropy: Coupling Efficiency for Energy and the Sustainability of Global Ecosystems

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Consideration of the property of action is proposed to provide a more meaningful definition of efficient energy use and sustainable production in ecosystems. Action has physical dimensions similar to angular momentum, its magnitude varying with mass, spatial configuration and relative motion. In this article, the relationship of action to thermodynamic processes such as the spontaneous increase in entropy of the second law is explained and the utility of action for measuring changes in energy and material distribution is promoted. In particular, the view that increases in entropy and action are equivalent to disorder is challenged. Given that the development of action states may be assigned an economic value and the various sources of free energy assigned a price, action theory may provide a novel mechanism for the economic allocation of resources. The importance of the diversity and redundancy of energy resources and work processes to optimize action is highlighted.

Keywords: *action; coupling; energy; entropy; exergy; sustainability; thermodynamics*

The extent of understanding of the relationship between energy and sustainability by the public remains poorly defined and variable. In spite of opinion among physical scientists that sustainability might be defined in thermodynamic terms (Addiscott, 1995; Bastianoni,

Nielsen, Marchettini, & Jorgensen, 2005; Dincer & Rosen, 2004; Hermanowicz, 2005; Norde, 1998), others consider that success in achieving sustainability will lie not in the physical science itself but rather in its application as modulated by economics and politics (Fleissner & Hofkirchner, 1997). In any case, an understanding of scientific issues by government decision makers or other managers, as well as by the public, is needed to prevent economic, environmental, or social costs that might result from the application of ill-advised technology and policy.

Much of the confusion regarding application of thermodynamics in society lies in poor understanding of the thermodynamic variables used for describing and quantifying energy. Mathematics is not unimportant, but its use can sometimes become the jargon of an elite, preventing more widespread social benefit from scientific research. On the other hand, even the term “thermodynamics” will elicit disdain from many people, despite the fact that its meaning suggesting “heat and movement” describes the everyday existence of everything on earth. Entropy, in particular, is a variable critical to thermodynamic theory, yet its properties remain elusive to the great majority, as well as to many involved in scientific research.

We will also assert that a succinct thermodynamic analysis of sustainability would be a useful goal that could help achieve a more prosperous, longer lasting society, particularly in the era of global warming and

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Bulletin of Science, Technology & Society Vol. 28, No. 3, June 2008, 260-272
DOI: 10.1177/0270467608316097
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climate change. We will advance a realistic approach to defining sustainability. However, because of the complexity of this scientific field, we acknowledge that this article may only initiate this approach, and we will welcome critical appraisal.

Perhaps at some risk of initial confusion, this article will attempt to unify the thermodynamic view of sustainability by introducing the concept of *action*. By no means new, action is a dynamic physical property of a system that encompasses the system's dynamic physical arrangements and configurations, as well as its inherent energy (Kennedy, 2001). We propose that quantifying changes in a system's action at different scales of motion during processes will provide a more useful assessment of sustainability than can be achieved by accounting for energy efficiency alone. Using natural systems as examples, we aim to illustrate how the realistic property of action, something we can see, may be used to assess efficient partitioning of a system's energy and thus to determine its sustainability. In learning about action from these systems, we will directly address the elements of sustainability outlined by Kinrade (2007) below.

Defining Sustainability

Despite an excess of vowels, the term sustainability has endured increasing use over the past two decades because the global society has come to realize the finiteness of our resources, strained by a growing population. As often pointed out, this term is itself open to varying interpretations, but in most cases sustainability implies the provision of useful products and services to humans over an extended time period. This is exemplified by the standard general definition of sustainable development, given 20 years ago at the Brundtland Commission in 1987:

Sustainable development is the development that meets the needs of the present without compromising the ability of future generations to meet their own needs. (World Commission on Environment and Development, 1987, p. 43)

Despite the self-interest of our species, we now realize the importance of all other living species and ecosystem services (if only for what they contribute to our lifestyle); efforts to quantify, evaluate, and protect these ecosystems have accelerated. More explicit definitions of sustainability address our interactive role with our environment. These definitions can be categorized into two different schools of thought, those of

“weak sustainability” and those of “strong sustainability,” indicative of the relative degree of human intervention implied (Kinrade, 2007). Weak sustainability allows natural capital to be substituted by “human-made” capital, whereas strong sustainability is more natural. A problem is that these valuations of each kind of capital are seldom precise, with the complexity and contribution of natural capital usually being undervalued, leading to its demise at the expense of excessive human capital. The premise of the strong sustainability concept is the converse—that natural capital is maintained by limiting the scale of such inputs of resources.

Daly (1991) suggested some practical guidelines for achieving strong sustainability, including that

1. Harvesting rates of renewable resources should not exceed regeneration rates,
2. Waste emissions should not exceed the renewable assimilative capacity of the environment, and
3. Nonrenewable resources should only be exploited at a rate equal to the creation of renewable substitutes.

Carefully examining these guidelines, one can recognize the emphasis placed on rates of resource use and regeneration and waste absorption, highlighting the importance of time as a factor in the concept of sustainability.

The laws of thermodynamics are regarded as critical to defining and achieving sustainable development, because they specify what energy and matter can and cannot do in our universe. In regard to energy resources, particularly important is the second law, which incorporates the concept of spontaneously increasing entropy and the arrow of time. In essence, the second law specifies the direction in which the universe as a whole is moving, often considered as toward a state of maximum separation of matter and minimum temperature. Fortunately, this “heat death” of the universe is extremely remote, so that the mean amount of renewable energy available to us on earth from solar radiation and geothermal activity is, for all practical purposes, constant. Indeed, we will argue below that on a sustainable earth, the entropy from 1 year to the next should be essentially constant, in stark contrast to the dire threat usually implied by the second law of thermodynamics.

Instead, the challenge is to use thermodynamics to help maximize the efficiency of renewable energy use so that its material resource capital can be maintained and harmful waste products, including chemical toxins and excess heat or radioactivity, can be minimized. Currently, the most popular thermodynamic

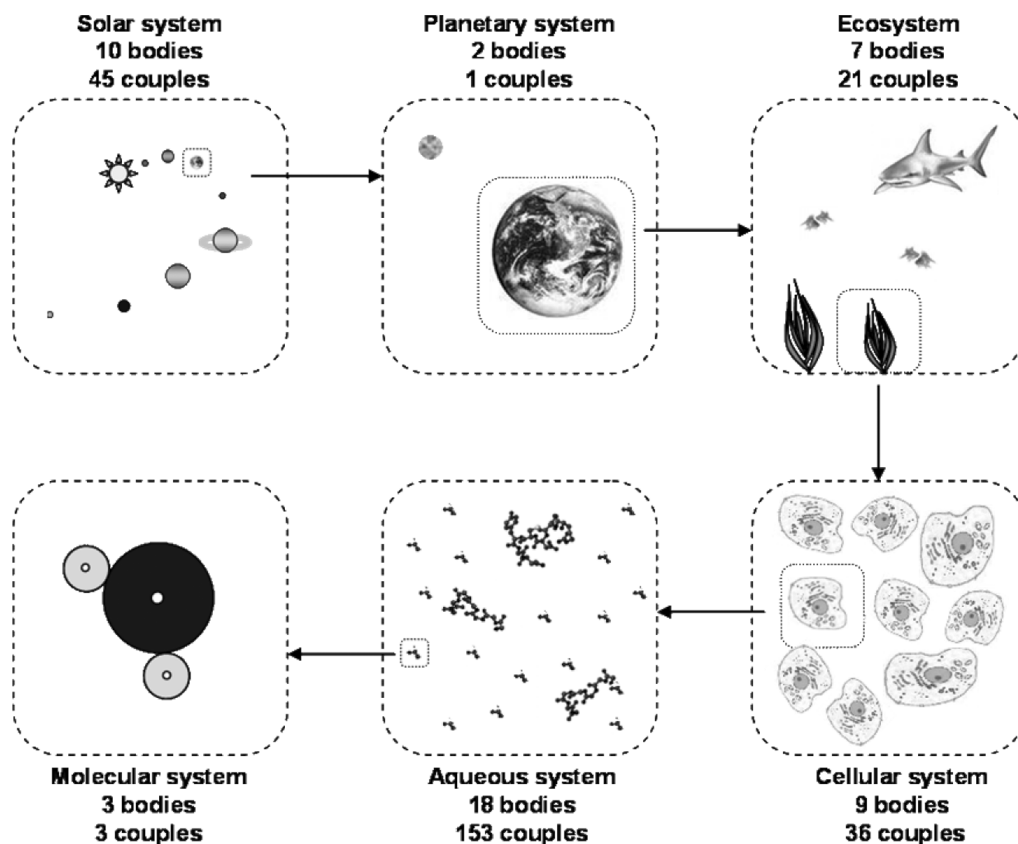


Figure 1. Action Occurs at all Scales Mediated by Various Couples

Note: The number of such coupled interactions varies according to $(n^2 - n)/2$, where n is the number of particles or bodies considered.

indicators for analyzing our performance against these sustainability factors are entropy and exergy. We propose that these indicators individually are insufficient and that an analysis of the physical property of action is a better way of valuing efficiency, maintenance of capital, and waste production.

An Introduction to Action Couples in Thermodynamics and Ecosystems

The laws of thermodynamics describe universally accepted truths about energy, such as its conservation and its tendency to be redistributed. Each of these laws can be interpreted in various ways, but here we state some common definitions and refer the reader to more substantial works on thermodynamics for fuller treatments.

The first law of thermodynamics states that energy can neither be created nor destroyed—it can only change in form. However, the second law is the most discussed. Although difficult to define uniquely, it gen-

erally relates to the spontaneity of processes in systems not at equilibrium. In 1865, Rudolph Clausius first formulated this law in relation to the flow of heat, which cannot occur spontaneously from a cold body to a hot body (Schmitz, 2007). Since, it has been reformulated in terms of entropy, which is accepted as increasing in the universe over time. Entropy producing processes are spontaneous, but the rate at which they occur is not specified. The third law states that the entropy of a system will approach a minimum value as that system approaches absolute zero temperature.

From the scientific point of view, the universe solely comprises matter and energy, two items declared to be interchangeable by Einstein. All systems are thus complexes of energy and matter, whose delineation depends on an observer, with arbitrary boundaries open to transfers of energy and matter. We point out that natural systems are characterized by nested scales of action, with that of smaller systems existing inside a hierarchy of larger systems, the properties of each scale contributing to the function of larger systems (Figure 1). We can

define a closed system as one with no matter transfer across its boundaries, and an isolated system with no transfer of either energy or matter.

However, both these definitions can only be considered as approximations. In fact, all ecosystems are open, the earthly systems essentially comprising living systems of the biosphere, acting in concert with the three abiotic systems, the lithosphere, the hydrosphere, and the atmosphere (representing solids, liquids, and gases) comprising overall the ecosphere.

In action theory, all systems whether living or non-living, are considered to consist of innumerable couples in nested scales. A couple consists of any two coherent bodies (nuclei and electrons, atoms, molecules, cells, animals, planets, galaxies), with interdependent movement in the available energy field. In his theory of gravitation, Newton showed how gravitational force could be considered primarily in terms of such couples, such as a planet and its central body, the sun, notwithstanding the fact that other bodies were perceived to affect the action of each gravitational couple.

The utility of couples is obvious in considering tidal phenomena on the earth, caused by the coupled movements of the earth, the moon, and the sun. Many other bodies actually influence the tides, but these effects are relatively minor, diminishing proportional to their spatial separation, affecting the spectral size of the quanta supporting the action and the overall intensity of the available energy field. In action theory, gravitation is a logical extension of electromagnetism, although the energy quanta involved are exceedingly small. In general, for bodies of similar scale, their movement will be influenced inversely proportional to the square of their radial separation, according to their capacity to perturb the universal energy field.

All such couples are able to either absorb or dissipate field energy with a simultaneous increase or decrease in their action, respectively. The field energy available for absorption or emission is capable of exerting a recoil force to matter; indeed, such field exchange of energy generates forces, from nuclear to gravitational. However, despite its small magnitude, we are most conscious of the radiation of the visible spectrum because of its daily variation.

Solar radiation at the earth's surface has been filtered of ultraviolet by the ozone layer at the top of the earth's atmosphere. Atmospheric oxygen near the earth's surface exists mostly as O₂, a molecular system coupling two oxygen nuclei having 16 electrons with two shared bonding electrons from the outer shells of each atom completing a molecular structure

sustained by the energy field of the local environment. By contrast, in the higher frequency energy field at the top of the earth's atmosphere, the stability of an oxygen system containing 27 coupled particles (3 oxygen nuclei and 24 electrons) called ozone is more favored. This energy field containing more ultraviolet radiation from the sun results in a shift in the local equilibria, increasing the electronic action of the couples so that O₃ is more favored.

Because action describes both the separation of the particles (r) and the motion of the couple by its momentum (mv), increased action requires an increase in the distance of separation of the couple or an increase in their relative speed or both. For any decreases in action, the opposite is true.

Mathematically, action (@) is a dynamic property with the same physical dimensions (M L² T⁻¹) as Planck's quantum of action (h):

$$@ = mrv = mr^2\omega$$

$$\omega = \frac{d\theta}{dt}$$

Here @ is the relative action of a moving body, m is the mass of the body, r is the radius of separation from another body, and ω is the angular velocity of the body (Figure 2; Kennedy, 2001), relative to the distant universe. Given energy has physical dimensions of the product of mass and velocity squared (M L² T⁻²), action is the product of energy and the period (time) of energy impulse (T).

Wherever there is a change in the partitioning of molecular energy into electronic, vibrational, rotational, or translational quantum states of an ensemble of molecules, there is a corresponding change in the overall action of the molecular system. Because action can be considered the product of mass by velocity (or momentum) and separation, its magnitude includes contributions from both the potential and the kinetic energy, varying with the total energy. The larger the quantum number (see Figure 2), the greater the action and the entropy of a molecular system. Entropy, that mysterious ever-increasing quantity said to govern the evolution of the universe, varies as a logarithmic function of the magnitude of the action expressed in units of Planck's quantum of action $h/2\pi$, for each degree of freedom of motion (Kennedy, 2000, 2001). This relationship will be explored in greater detail later.

Each unit of action in excited electronic states needs field energy with quanta of larger magnitude to sustain the motion of the couple when ultraviolet or light quanta

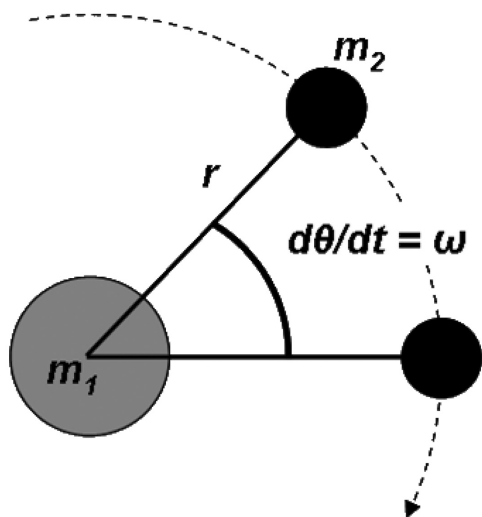


Figure 2. The Action of a Moving Particle Depends on Mass (m), Separation (r), and Velocity (v or $r\omega$)

Note: Because measurement will perturb either the radius or the velocity, with reference to an arbitrary reference frame, quantum mechanics was forced to proclaim the *uncertainty principle* concerning the position or momentum of atomic particles like electrons with low inertia. However, the action (the product of the momentum and position) of an electron is always an exact multiple of Planck's quantum of action, $h/2\pi$, known as the quantum number.

are absorbed. This is because of the closeness of the couple and the greater magnitude of changes in $1/r^2$, compared to the smaller size of the quanta of field energy needed to excite and sustain the action of couples more separated, as in excited vibrational, rotational, and translational states. In correcting the imbalance of intermolecular forces caused by the absorption of these larger quanta, there is a spontaneous tendency, as a result of collisions, for the newly absorbed field energy to be redistributed from excited electronic states as a cascade of changing vibrational, rotational, and translational action states, thus maximizing the action and entropy overall. Such a partitioning of energy into smaller quanta as the molecular system approaches equilibrium minimizes the overall stresses in the system by balancing the forces exerted as torques by the energy field on the different degrees of freedom of motion of the couples of the molecular system (Kennedy, 2001).

The Significance of Entropy and its Relationship to Action

Action provides a unifying principle for Clausius' thermal and Boltzmann's statistical interpretations of entropy (Kennedy, 2000).

Clausius found that heat energy could not be converted to an equivalent amount of work energy, if the temperature remained constant. To indicate the energy identified as not available to do work, he invented the term entropy (S), which he defined as the integral of the heat (Q) absorbed reversibly from absolute zero to the temperature of the system (T).

$$S = \int_0^T dQ/T$$

Classically, entropy was not defined with units of energy, because its magnitude was found to vary with temperature (i.e., entropy equals energy per unit temperature, joule per kelvin). In action theory, this expression of entropy is simply considered as a dimensionless capacity factor, the ratio of the cumulative heat needed to raise the temperature to T , divided by the absolute temperature, the latter being considered an energy intensity factor. By analogy with this definition, Boltzmann's constant k is also a dimensionless factor converting temperature as degrees Kelvin into joules of kinetic energy.

By contrast, Boltzmann's view of entropy ($S = k \ln \Omega$) was statistical, related to the number Ω of complexions or configurations existing in a system of many particles. We can point out here that the statistical view is equivalent to considering the action (Kennedy, 2000), also a simple function of frequency of occurrence or concentration, because this determines the radial separation of particles. Given their lower probability, high energy states of a molecule must occur with lower frequency or concentration at equilibrium than a lower energy state at the same temperature. On one hand, the reversible work done by the field of the larger number of ground state molecules, whose individual action decreases whenever an excited molecule reverts to the ground energy state, reducing their separation must be equal to that done on the field of the excited molecules whose translational action increases and vice versa when the reaction is reversed. On the other hand, the disappearance of a molecule of either kind results in the release of a quantum of energy previously required to sustain the molecule in the field. In this way, the force fields associated with these changes in action state can be balanced at equilibrium.

The positive variation of entropy with temperature is also mimicked by increases in action, by its effect on the molecular velocity (varying with $T^{0.5}$). As a result, considering action is equivalent to the statistical approach, but it provides a more realistic model of the system as a complex of coupled particles.

Boltzmann and Gibbs, in founding the discipline of statistical mechanics in the 1880s, proposed entropy as a statistical distribution of molecules to physical states of different energy,

$$S = -k \sum p_i \ln p_i$$

Here k is Boltzmann's constant, and p_i is the probability of a particular energy state with $\sum p_i$, but where different states may have different probability.

For equal probability of each state with a total of Ω states, the probability $p_i = 1/\Omega$ and the total $\sum p_i$ must equal 1. Thus,

$$S = k \ln \Omega$$

This is the famous conclusion attributed to Boltzmann on his tombstone, although it should be observed that Max Planck introduced the concept of Boltzmann's constant k as the quotient of the gas constant R and N , Avogadro's number.

We can relate this action approach to the absorption of a photon of light by a pigment molecule in photosynthesis, where both its electronic action and its entropy increases just as the potential or free energy of the system. This is because the electronic action in the absorbing molecule is now excessive compared to the action of complementary molecular couples associated with vibrational, rotational, and translational motion for the system to be at equilibrium. As a result of collisions, a spontaneous reordering of the energy field must now occur to bring the forces involved with these freedoms of motion into balance. This increases the overall action of the system because a repartitioned quantum of electronic energy can sustain or buy much more action for the motion of these other couples in action states separated by quanta, with increasingly lower frequency.

It is the tendency to increasing action that is the real basis of the second law of increasing entropy. However, the efficient cause of the second law is the unbalanced forceful interaction of energy with matter at different scales of action and increasing entropy is only a final cause or result. That the energy levels of the translational action states are much more closely spaced than those of the electronic states indicates the decreasing size of the quanta needed to sustain increasing levels of action.

Given the forceful tendency of internal energy to change the action of the system as a whole, there is a real sense in which an initial nonequilibrium state of higher free energy following absorption of a quantum of light is more chaotic and disordered than the more relaxed state of higher action and entropy toward which

the system evolves. In general, higher overall action and entropy indicates a more relaxed state with less "free energy" or tendency for further spontaneous change.

Philosophically speaking, this rational reordering of the energy field is profound, because it is the very basis of the arrow of time. The reverse process that would cause unbalanced forces or torques to spontaneously develop required by a reversal of time is logically absurd, actually defying the principle of conservation of momentum. Despite the oft-made claim that Newtonian forces are time reversible, this is not the case when they are considered in the context of a cascade of forces of action exchange acting to correct a state of imbalance. Statistical mechanics may seem to allow time reversal by a random allocation of particles reversing the law of entropy increase, but the random forces of the energy field ensure that such a result is impossible. The only means for a system of particles to "spontaneously" decrease its entropy is to remove the dispersal force of field energy by inserting a cold finger at a much lower temperature.

It is unfortunate that entropy has itself been equated to disorder, when, realistically, for matter, the opposite is the case. The highest state of entropy actually corresponds to the most ordered distribution of energy in the molecular system. This paradox has needlessly confused students for some 150 years since the concept of entropy was introduced. The state of maximum entropy and minimum free energy of a system corresponds to that where the power to do work is distributed most evenly across the system so that stresses are equalized. So increasing entropy is equivalent to relaxation, whereas lowering entropy is equivalent to stress. This is not to say that one state is preferable to the other: As many company directors will agree, employees under some stress and pressure will produce work. But beyond a certain point, they may suffer a nervous breakdown, analogous to a nonliving system in a chaotic state as a result of energy overload, whereas employees relaxing on holidays do not.

For a discussion of energy efficiency in sustainable ecosystems, it is important to realize that the thermodynamic entropy measures the energy required to sustain the motion of molecular degrees of freedom. For example, the thermal energy needed to activate the internal degrees of freedom of water (electronic, vibrational, rotational, and translational) corresponds to the cumulative increase in the entropy of water at a particular temperature T . Thus, the heat absorbed gradually raising the temperature of ice from zero kelvin to its freezing point, then to melt it into the rolling transient clusters found in liquid water, and then to degrade the clusters evaporating individual water molecules as vapor, all contribute to its entropy content.

In action theory, the entropy (designated as S) is a cumulative heat capacity factor for the amount of energy required for the system to be at a particular temperature T . At equilibrium, ST then indicates the total thermal energy required for the action of all degrees of freedom of motion of the water to be sustained at T . If S is considered a dimensionless factor generated by dividing an extensive quantity of energy by the intensive energy T (joule per kelvin), then the factor T is a statistical surrogate for the value of the equalized torques exerted by the energy field on each degree of freedom of motion of the molecular system.

However, we do not consider the thermal energy required to sustain even higher order motions of molecules, such as the mass molecular flow of convection, advection, and turbulence, where heat is absorbed by a system without causing the temperature to rise, as contributing to entropy, despite this energy clearly contributing to higher order action. One anticipates that these higher order motions correspond to partitioning of energy to even smaller quanta in the energy field. Ultimately, such absorption of heat can contribute to increased gravitational action, as observed in the hydrological cycle where sea water is evaporated (an entropy increase), convected to higher altitudes (gravitational action increases but molecular entropy and action remain the same for adiabatic expansion as T and velocity fall, while spatial separation increases), condensation, (entropy decrease) and deposition on the land (gravitational action decrease but thermal action increase; Figure 3). All these energy transactions with increases and decreases in entropy correspond primarily to local balancing of the forces exerted by the energy field on matter such as water. Overall, there is an increase in entropy during such spontaneous processes, but there is nothing to prohibit the entropy of individual components in the system from increasing or decreasing. The second law of entropy increase refers to the whole system and not to its individual components.

The hydrological cycle illustrates the advantage of considering action together with entropy, providing an improved understanding of the meaning of entropy as a physical property of a system. We should also consider that, in practical terms, we would expect the total entropy of the matter of an ecosystem on earth to remain the same from one year to the next, although there will be spatial and temporal variations in action and entropy, dependent on variable environmental factors such as the season or the latitude.

Despite the negligible annual change in the entropy and action of the earth's surface material, there is a substantial rate of increase of the entropy of the radiation

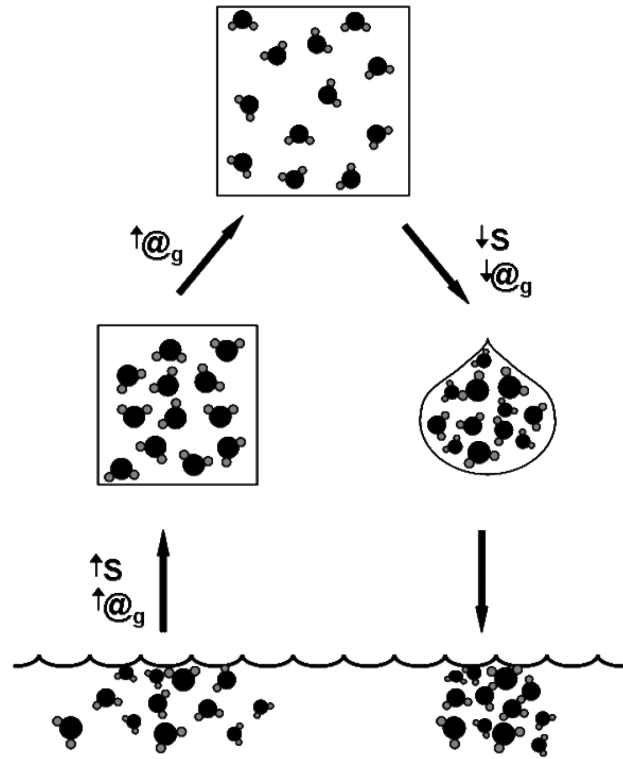


Figure 3. Changes in Entropy (S) and Gravitational Action ($@_g$) During the Hydrological Cycle

Note: Water increases its entropy during vaporization, but this tendency is reversed in the atmosphere because of an initial adiabatic expansion with height, and expanding at such a rate that the action and entropy remain constant; but condensation then substantially decreases the action and entropy with evolution of heat, as the water precipitates. However, the gravitational action increases as water rises in the atmosphere and decreases as it precipitates.

absorbed and reemitted by the earth's surface, as given by the equation following,

$$\frac{\delta s}{\delta t} = \frac{Q}{T_i} - \frac{Q}{T_s}$$

given that Q represents the solar energy absorbed by the earth's surface per second effectively at the temperature of the sun T_s and then eventually reemitted at the temperature of the earth T_i (Kennedy, 2001). This estimate of entropy generation neglects any short-term variation in the net storage of solar energy on earth as fossil fuels or release of energy by radioactive decay or frictional processes. However, this increase in the entropy of radiation does correspond to a 20-fold increase in the number and the total action of the quanta and could be considered to be an increase in its

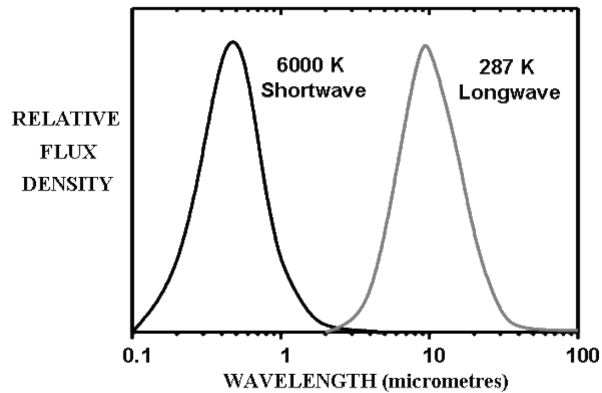


Figure 4. Spectra of Solar and Terrestrial Radiation, Normalized for Peak Energy Flux Density With Wavelength (Adapted From Reifsnnyder & Lull, 1965)

Note: To maintain balance, the total flux of solar energy and momentum received by the earth as impulses must equal the flux of energy and momentum it emits. However, because the earth's average emission temperature is one twentieth that of the surface of the sun, the average wavelength of the quanta emitted is 20 times as long, and the number of quanta is 20 times as many.

disorder. Each quantum of energy is considered as having an action of 1.

But this ongoing process has not generated an increase in disorder on the earth. On the contrary, radiation emitted at 6,000 K by the sun (Figure 4) constantly allows new free energy to be generated by absorption of quanta in the surface materials of the earth. These absorptions cause forceful electronic stresses, producing chaotic states that are eventually dissipated into the numerous action processes of the ecosphere. This process must result in reemission of the same amount of energy but at a lower average temperature of about 300 K. In general, the intensity of the action processes sustained by this energy flow are beneficial for life on earth, including variations in the climate, the meteorological processes in the atmosphere producing winds and weather, the ocean currents, the hydrological cycle and rainfall, photosynthesis, and all the life processes of the biosphere, the latter directed, as originally pointed out by Schrödinger (1944), via the highly diverse informational content of DNA.

Because of their processes of adaptation, and this constant flux of free energy, healthy natural ecosystems will be largely self-sustaining and be able to export entropy production to the atmosphere or cooler latitudes, without degrading themselves or adjacent systems. Nevertheless, there will be constant local

changes in action and entropy as a result of environmental fluctuations and other perturbing factors; the study of these fluctuations, and how they are balanced and overcome, is essential to obtain an understanding of sustainability. Action theory (Kennedy, 2001), based on some reinterpretations of classical and statistical thermodynamics, was advanced as a new approach to help us better understand these energy fluctuations and the consequent stability of ecosystems and their resilience.

The Relationship of Action to Exergy and Sustainability

Following on our discussion of thermodynamics above, during production of commodity goods or services, some energy is conserved in a form that is able to support other work later. For example, in photosynthesis, the free energy generated in the electrons of the photosystems is conserved by the subsequent conversion of relatively high entropy substances such as carbon dioxide and water to lower entropy substances such as sugars and oils. For such chemicals, we recognize that a high proportion of energy is necessary to maintain these reactants "as is" internally; these energy-conserving compounds have a relatively high content of the energy designated as enthalpy, H , associated with electronic, vibrational, or rotational action. On the other hand, we recognize that during a chemical process involving rearrangements of matter, energy is also needed to sustain the external physical molecular arrangement "as is." This energy is required to sustain higher scales of motion such as translational action and is also available for transfer outside the molecular production system if a pressure or temperature gradient exists, both contributing to an entropy increase during a reaction externally.

Thus, during these rearrangements of matter, we may have two types of energy that cannot be used for work in a system at equilibrium, internal bonding energy usually associated with quanta of higher frequency and external energy of dissociated molecules, usually of much higher entropy but of much lower frequency. However, to the extent that the quanta associated with these different forms of internal and external action are not equilibrated for the current temperature in a set of reactants and products, there is a capacity to do work as long as the imbalance is maintained. Imbalance is eventually reflected in the concentration of reactants and products, associated with the translational action.

These forceful rearrangements in the partitioning of energy between internal and external degrees of freedom

are summarized in the equation suggested by Willard Gibbs for the free energy change (ΔG) in a spontaneous reaction as equal to the change in enthalpy (ΔH) less the change in the entropy by temperature:

$$\Delta G = \Delta H - T\Delta S$$

If ΔH is negative (i.e., energy is absorbed by the surroundings or pressure–volume work is performed externally) or if the entropy of the system increases, work can be done.

Free energy is not a separate kind of energy. It is the work possible ($-\Delta G$), purely as a result of the degree of the imbalance of the forces sustaining the action of internal and external degrees of freedom at temperature T .

Sustainability implies a continued generation of services or capacity to do work over time. Indeed, if considered as the product of energy or work and time, its physical dimensions are the same as those of action. However, the more efficient a process in an ecosystem, the less energy is expended for a given return in action, leaving more of the flux of energy for beneficial action. The greatest efficiency in the use of energy in a chemical process occurs where the imbalance between these energy fields corresponds to a quantum of energy released during each chemical transformation exactly matching that required by the coupled work process. Inefficiency occurs when the quantum emitted is much greater than the quantum of energy required, and there is a mismatch of the forces.

Accounting of the different types of energy and its efficient use has been formalized recently as *exergy* analysis, a theoretical concept that considers properties such as entropy, mechanical work potential and chemical potential to measure what is considered the amount of useful energy available as a system evolves to a reference state (Bastianoni et al., 2005; Rosen & Dincer, 2001). This portion of “useful” energy, termed exergy, has been defined as:

$$Ex = S(T - T_0) + N_k(\mu_k - \mu_0) - V(p - p_0)$$

(given in Rosen & Dincer, 2001)

$$Ex = (U - U_0) + p_0(V - V_0) - T_0(S - S_0)$$

(given in Tsatsaronis, 2007)

N_k is the number of moles of a substance k , μ_k is the chemical potential of substance k , V is volume, p is pressure, and U is the internal energy. The subscript 0 indicates the values of those properties for a reference level such as the surrounding environment. Thus, for a

system evolving by chemical changes, exergy must be equivalent to Gibbs definition of free energy.

Exergy has been classified as three kinds (from Bastianoni et al., 2005):

- The exergy of the output of a process (Ex_{out})
- The exergy stored in a system (Ex_{in})
- The exergy required to drive a process or a system (Ex_{in})

Note that exergy does not measure efficiency but is only a potential. In fact, Bastianoni et al. (2005) discuss the use of four different efficiency indices involving exergy, including the “single process efficiency” index, Ex_{out}/Ex_{in} , and an index describing the level of organization supported by a unit exergy input, Ex_s/Ex_{in} . A single process efficiency relationship has been used to evaluate a number of thermal and industrial processes (Ayres, Ayres, & Martinas, 1998).

From the viewpoint of action analysis there are difficulties with exergy, and all process analyses regarding the definition of the desired scales and the energy needs for their sustenance. A problem relates to defining the distribution or organization of matter of the system including inputs and outputs, acknowledged as a limitation of exergy analysis (Ayres et al., 1998; Hermanowicz, 2005; Jorgensen & Nielsen, 2007). Ayres et al. (1998) recognized that exergy analysis gave an implicit indication of the chemical arrangement of waste products in a chemical production process but did not go further to describe the physical arrangement of outputs, such as concentration. Hermanowicz (2005) integrated Boltzmann’s concept of entropy to more explicitly describe the physical arrangement of waste matter in exergy analysis. Jorgensen & Nielsen (2007) also addressed this issue by incorporating an index of information (related to entropy through the definitions of Shannon & Weaver, 1949) to describe the energy involved in an ordered ecosystem.

We propose that action theory may be able to overcome limitations of exergy analysis that must be restricted to calculations involving energy. Indeed, it could be debated whether exergy adds anything unique to energy efficiency analysis when free energy will often suffice. However, exergy may have the advantage of drawing attention to forms of renewable work potential such as windpower not obviously included by the concept of Gibbs free energy. Indeed, windpower involving inertial effects from the mass transport of air with respect to a stationary mill braced in the earth is a higher scale of action than the molecular action considered as

involving entropy. The molecular collisional forces acting to transfer momentum so generating the action of the blades of the mill are no different than those involved in entropy generation in molecular thermodynamics. Equally, gravitational potential energy of water such as that used in hydroelectric power is not obviously equivalent to the free energy of chemical systems. However, changes in gravitational action are clearly involved in converting this form of work potential to electrical energy in a dynamo.

What would we lose by replacing the term exergy by action potential (Kennedy, 2001)? Both terms indicate a potential to do work, by increasing or sustaining action over a period of time. The interaction of matter with its energy field defines the forces that act in the system and the action generated in the various degrees of freedom of motion is our actual point of interest. Action can, therefore, be used to define or measure the desired output as the very effect we wish to bring about. Recall too, that action is dimensionally the product of the energy required and the time required for doing it. In fact, changes in action are our focus of interest and will better define the efficiency of our use of energy.

The efficiency of a process of action increase at a particular scale in products of the system can, therefore, be determined by measuring the total amount of energy input (E_{in}) and the time t over which it is applied, indicated by the difference between the initial action $@_o$ of the component a of the system and the final action $@_t$ for this scale of the system. This conclusion presumes that in an efficient process, the available useful energy will be directed to selected actions rather than distributed at random. This also suggests the key role of information in the system, selecting defined actions by redistributing the useful or free energy of the system in seeking equilibrium. The extent to which the free energy is randomly dissipated in other processes not specifically selected indicates its degree of inefficient use and the quality of the information inherent in the system.

Thus, the efficiency for a process at scale a in a selected system can be estimated as:

$$\text{Efficiency} = \frac{@_t^a - @_o^a}{E_{in} \cdot t}$$

When the action of all degrees of freedom of motion (a, b, c, \dots, z) is considered, the cumulative efficiency of the change in the desired action states can be estimated by comparison with the increase in action at all scales. It is important to note that whereas total energy is always conserved, and its efficiency of

use to sustain some action or other is actually 100%, the desired action as a proportion of that sustained by the total energy flux is a variable, dependent on the pattern of partitioning of the energy to different scales of motion.

Furthermore, it must be borne in mind in such an estimation that the relationship between the increase in action and the entropy increase and hence the energy requirement to sustain the system in static molecular systems is logarithmic (Kennedy, 2000). That the additional energy required to generate additional action decreases exponentially implies a process for generating action always proportional to its current magnitude. Apparently, as a result of cooperative effects in systems with many particles of matter, less energy is required for each cumulative increase in action.

Optimizing Action in Ecosystems for Efficiency and Sustainability

The chemical and physical morphologies (action states) and reactions (rearrangements of the action state) of a system directly result from forces applied by the local energy field. The key difference between biotic and abiotic systems is the enhanced ability for self-organization by biotic systems. When an abiotic system is subject to an energy gradient, it will tend to rearrange to a more relaxed set of action states dictated by the energy field (Kennedy, 2000) in which energy gradients are dissipated at the maximum rate possible (e.g., as observed by Paltridge, 2001), limited by the quality of the available coupling mechanisms.

The maximum rate of entropy production conceivable for solar energy could only occur if energy in equilibrium with the sun's surface was absorbed by the earth and instantaneously reemitted at the temperature of the earth. In fact, this energy dissipation takes time, depending on the ability of the coupling mechanisms at the earth's surface to store the free energy generated by sunlight in conservative materials that can be used later. The world's forests are an obvious example of such conservation mechanisms, or the much older fossil fuels stored in geological formations. Obviously, arid deserts increase the entropy of the absorbed radiation faster than verdant forests, producing large quantities of lignin and cellulose.

So, the current debate regarding different points of view that propose either maximum or minimum rates of entropy production, as favored, may actually be misplaced. A more relevant requirement for sustainable life may be that the rate of entropy production be optimal under the constraints imposed. Certainly, this

would seem to be the basis for the Kyoto protocol and other current efforts to reduce the rate of global heating. Most important here is the extent to which we can control the rate of action and entropy production by selecting the most suitable coupling mechanisms, as nature has already done during biological evolution

To a certain extent, abiotic systems participate in such conservation of free energy or action potential as in the hydrological cycle and the gravitational potential generated by precipitated water in elevated glaciers or lakes. Soil erosion is a product of the work potential stored in this way. By contrast, biotic systems can manipulate the energy field to arrange matter producing stressed, higher action states for the specific purpose of such energy storage. Thus, although ordered abiotic action systems such as convection cells collapse rapidly when the external temperature–energy gradient is lowered or removed, living systems frequently continue to sustain their order by using stored internal (chemical) gradients. Natural selection has ensured that energy is used efficiently to sustain life processes as its availability is not always assured.

As mentioned earlier, systems store or dissipate energy through an increase or decrease in *action*, respectively. Living systems efficiently manipulate energy (and action) via the diversity and redundancy of couples, and the timing and resonance of coupling events, in a manner that seeks to ensure growth, reproduction, waste removal, and ultimately sustainability. Living systems are, above all, cooperative.

For the majority of ecosystems on earth, solar radiation is the primary source of energy. This arrives at the earth's surface with a spectral distribution mainly in the ultraviolet and visible range with near infrared but is degraded following absorption by the earth to longer wavelengths that are able to interact with couples of appropriate scales (Figure 5).

The arrangement of matter in living systems is very complex and diverse. Paradoxically, both diversity and redundancy are essential for the survival of a living species or system. Sustainability requires finding the optimum of each: Whereas diversity defines the energy frequencies that can be captured, redundancy increases the probability that a particular frequency will be captured.

Diverse coupling arrangements at different scales (radii of separation and momentum) are necessary to store (absorb) and to dissipate (emit) the diverse energy spectrum arriving in the ecosystem. The greater the diversity of couples in a system, all of slightly different action scales, the greater the probability that any energy frequency can be absorbed. An example of this is the use

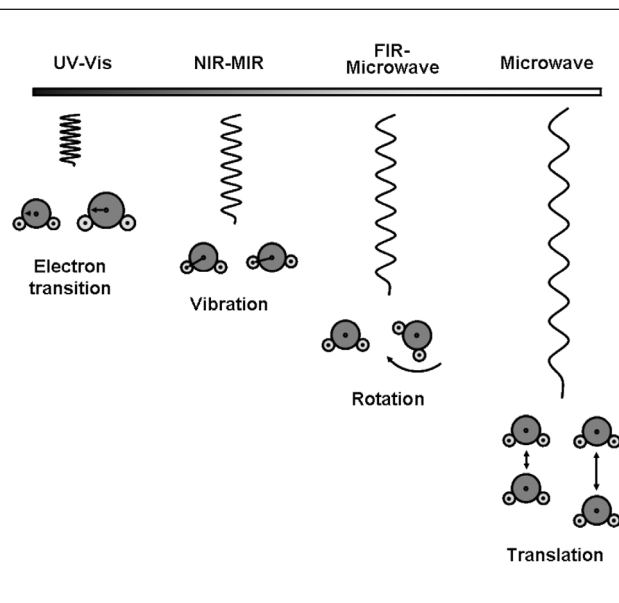


Figure 5. Energy Spectrum and Interaction With Couples of Different Scales (Kennedy, 2001)

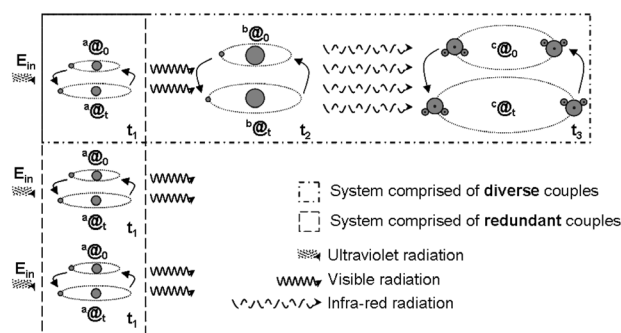


Figure 6. The Interaction of Energy With a System Containing Diverse Couples, Showing an Energy Cascade, and a System Containing Redundant Couples

of anthocyanins and other colored pigments to collect sunlight energy at different wavelengths to chlorophyll, which then gets distributed back to the reaction center. This principle has also been used to design fourth generation photovoltaic cells that maximize the conversion of the solar energy spectrum to electrical potential.

Energy that is absorbed by a couple for a period of time and then reemitted at a longer wavelength can also be reabsorbed by a different couple (Figure 6). The total residence time (time of storage) of the energy in that system will, therefore, increase if diverse couples are present, increasing the opportunity to do work. In living systems, the diversity of energy pathways used to do work is reflected in the genetic code and the availability

of a sufficient range of proteomes and other higher order structures derived from these (e.g., functional organelles, cells, communities of cells, or higher organisms) to provide the coupling mechanisms to achieve these objectives.

This highlights the potential energetic advantage of biodiverse cropping systems (including crop rotations) compared to a monoculture. The presence of diversity coupling pathways are also important for the buffering of energy fluctuations, as alternative pathways can then be switched on or off to supply or absorb energy, depending on the incoming frequencies.

Thus, when translating these observations to designing efficient artificial processes, we should harness all parts of the energy spectrum available to do useful work and remove pathways that will couple the energy to “useless” work. This may involve creating a number of different products or services that are useful from the one energy source, more effectively using “waste energy.”

However, the role of couple redundancy must also be acknowledged. If there is a high intensity of a certain frequency of energy, couples that can use that energy for work will be more widespread in that field (e.g., chlorophyll and leaves in light environments, sulfur-reducing bacteria in dark anaerobic environments).

As humans, there are certain goods and services that we desire in large quantities, and consequently we have learned to maximize the coupling pathways that provide these goods. In agriculture, for example, the conversion of abundant fossil fuels into specific energy frequencies tailored to our favored genetic species is dominant. This includes the use of highly soluble fertilizers for grain production and highly digestible feed for meat production.

Ultimately, though, the exhaustion of fossil fuels may reveal that the current abundant coupling pathways are not as efficient when we are forced to rely on energy sources of different frequencies. Action analysis may provide a means of comparing alternatives. One example of an alternative coupling pathway is the use of nitrogen-fixing microorganisms to provide the nitrogen requirement of a crop, instead of the industrial production of nitrogen fertilizer via the Haber process.

Finally, redundancy should be recognized as essential for ensuring a wide distribution of coupling potential, essential to diversity. Redundancy is important in the case of extinctions of a certain species, such that the potential for a particular process is still available.

Because many work processes in systems are resonant, diurnal, and seasonal, the timing of coupling input

energy to a useful work process is also very important. An energy input can either amplify or inhibit the efficiency of a continued work process. Examples include the operation of a piston in a motor engine, with either smooth operation or pinking; the use of continuous lighting in a sometimes-empty building; or proper or improper timing of fertilizer inputs to a crop.

Obviously, there will be local changes in action and entropy as a result of environmental fluctuations such as seasonal or other perturbing factors. These effects will be mirrored in the rate of production of renewable energy. In such systems, a monoculture energy economy relying on the use of only a single energy source can be a risk to the sustainability of a society.

We will conclude by reiterating from a thermodynamic point of view that a sustainable ecosystem has no significant change with time in either its total action or its entropy. It is anticipated that the framework provided here will enable a more realistic analysis of our current systems for coupling available energy to useful action and provide the logic to improve these systems and achieve sustainability.

References

- Addiscott, T. M. (1995). Entropy and sustainability. *European Journal of Soil Science*, 46, 161-168.
- Ayres, R. U., Ayres, L. W., & Martinas, K. (1998). Exergy, waste accounting, and life-cycle analysis. *Energy*, 23, 355-363.
- Bastianoni, S. B., Nielsen, S. N., Marchettini, N., & Jorgensen, S. E. (2005). Use of thermodynamic functions for expressing some relevant aspects of sustainability. *International Journal of Energy Research*, 29, 53-64.
- Daly, H. E. (1991). Elements of environmental macroeconomics. In R. Costanza (Ed.), *Ecological economics: The science and management of sustainability* (pp. 32-46). New York: Columbia University Press.
- Dincer, I., & Rosen, M. A. (2004). Exergy as a driver for achieving sustainability. *International Journal of Green Energy*, 1(1), 1-19.
- Fleissner, P., & Hofkirchner, W. (1997). Entropy and its implications for sustainability. In I. C. Dragan, M. C. Demetrescu, & E. K. Seifert (Eds.), *Implications and applications of bioeconomics: Proceedings of the Second International Conference of the E.A.B.S., Palma de Mallorca, 1994* (pp. 147-155). Milan: Edizioni Nagard.
- Hermanowicz, S. W. (2005, December 1). *Entropy and energy: Toward a definition of physical sustainability*. Water Resources Center Archives (Working Papers, Paper swr_v2). Retrieved March 1, 2008, from http://repositories.cdlib.org/wrca/wp/swr_v2
- Jorgensen, S. E., & Nielsen, S. N. (2007). Application of exergy as thermodynamic indicator in ecology. *Energy*, 32, 673-685.
- Kennedy, I. R. (2000). Action as a dynamic property of the genotype \times environment interaction: Implications for biotechnology. *Acta Biotechnologica*, 20, 351-368.
- Kennedy, I. R. (2001). *Action in ecosystems: Biothermodynamics for sustainability*. Baldock, UK: Research Studies Press.

- Kinrade, P. (2007). Toward a sustainable energy future in Australia. *Futures*, 39, 230-252.
- Norde, W. (1998). Energy and entropy: A thermodynamic approach to sustainability. *Environmentalist*, 17, 57-62.
- Paltridge, G. W. (2001). A physical basis for a maximum of thermodynamic dissipation of the climate system. *Quarterly Journal of the Royal Meteorological Society*, 127, 305-313.
- Reifsnyder, W. E., & Lull, H. W. (1965). *Radiant energy in relation to forests* (p. 111). Technical Bulletin No. 1344. Washington, DC: U.S. Department of Agriculture.
- Rosen, M. A., & Dincer, I. (2001). Exergy as the confluence of energy, environment and sustainable development. *Exergy, an International Journal*, 1(1), 3-13.
- Schmitz, J. E. J. (2007). *The second law of life: Energy, technology, and the future of earth as we know it*. Norwich, NY: William Andrew.
- Schrödinger, E. (1944). *What is life?* Cambridge, UK: Cambridge University Press.
- Shannon, C. E., & Weaver, W. (1949). *The mathematical theory of communication*. Urbana: University of Illinois Press.
- Tsatsaronis, G. (2007). Definitions and nomenclature in exergy analysis and exergoeconomics. *Energy*, 32, 249-253.
- World Commission on Environment and Development. (1987). *Our common future*. New York: Oxford University Press.
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