Enhancing Ecological and Environmental Understanding with Exergy: Concepts and Methods

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Abstract: To understand ecological systems and environmental impact, techniques can be used which combine thermodynamics with environment and ecology. Most assessments consider thermodynamics via energy, but many feel that ecological and environmental factors are better understood through exergy. One rationale is that exergy, not energy, is often a measure of the potential for ecological and environmental impact. Here, existing analysis techniques are reviewed which integrate exergy and ecological and environmental factors, including exergy-based ecological indicators, exergy-based life cycle analysis and environomics. The goals of most such techniques include improving understanding of the impact on ecological systems and the environment of processes and the determination of appropriate ecological and environmental improvement measures.

Keywords: Ecology, environment, energy, exergy, water, efficiency, sustainability

1 Introduction
Environmental and ecological impacts are important factors in design. Assessments of environmental and ecological impact often consider energy. But many note that the thermodynamic quantity exergy, which stems from the second law of thermodynamics, is often a consistent measure of the potential for environmental or ecological impact, while energy is not. Exergy is useful in understanding and assessing ecological systems and their wellness (Szargut et al., 2002; Szargut, 2005; Jorgensen, 2000; Jorgensen and Fath, 2004), environmental impact (Sciubba, 1999; Tribus and McIrvine, 1971; Rosen and Dincer, 1997a, 1999; Gunnewiek and Rosen, 1998; Rosen, 2002a), non-renewable resource depletion (Szargut et al., 2002) and sustainability (Dincer and Rosen, 2007). Consequently, many recommend that environmental and ecological assessments be based on exergy.

Several exergy-based environmental and ecological analysis techniques have been developed. They help determine the appropriate allocation of resources for environmentally responsible or improved design and operation. Existing exergy-based environmental and ecological techniques include environomics, exergy-based industrial ecology and exergy life cycle assessment. These approaches identify as important the exergy of a system and its inputs and outputs.

Maintaining ecological integrity is important but complex (Kay and Regier, 2000; Jorgensen et al., 1995). Understanding ecological integrity is relevant in regional and global efforts aimed at restoring environments and protecting health. Accounting for nature’s contribution to industrial activity is important in determining its impact and sustainability. Decisions based on assessments that ignore nature significantly deteriorate the ability of ecosystems to provide the goods and services necessary for human activity. Here, relations between exergy and environment and ecology, and corresponding analysis techniques, are reviewed.

2 Exergy
Thermodynamics describes system performance and efficiency. Conventional thermodynamic analysis is based primarily on energy and its conservation. An energy analysis of a process or system essentially accounts for the energy exiting (with products and wastes) and entering, and efficiencies are evaluated as energy ratios. But energy efficiencies do not generally assess how nearly performance approaches ideality and are consequently often misleading. Also, factors which cause performance to deviate from ideality (i.e., thermodynamic losses) are often not properly described with energy. Exergy provides an approach which circumvents these concerns.

Exergy analysis (Dincer and Rosen, 2007; Gaggioli, 1983; Moran and Shapiro, 2007; Kestin, 1980; Moran, 1989; Kotas, 1995), a thermodynamic analysis technique based on the second law of thermodynamics, overcomes many of the shortcomings of energy analysis. Exergy efficiencies provide a true measure of how nearly performance approaches ideality, and identifies properly the
causes, locations and magnitudes of inefficiencies. Also, exergy analysis indicates theoretical limits imposed on a system, which show that a real system can not conserve exergy and only a portion of the input exergy can be recovered, and practical limits by evaluating losses that directly measure lost exergy.

The exergy of an energy or material quantity is a measure of its usefulness or quality. Exergy can be consumed but energy is conserved. By providing an illuminating, rational method for meaningfully assessing and comparing systems, exergy analysis can assist in improving designs. Increasing recognition of the usefulness of exergy by industry, government and academia has been observed, with applications reported in electricity generation, cogeneration, heating, thermal energy storage, and chemical and metallurgical processes, countries, etc. (Dincer and Rosen, 2007; Szargut, 2005; Sato, 2005).

Exergy is evaluated with respect to a reference environment, which is in theory in stable equilibrium, with a constant intensive state (temperature pressure, chemical potentials) and all parts at rest relative to one another. The reference environment acts as an infinite system, and is a sink and source for heat and materials, but chemical reactions do not occur between the environmental components. The exergy of the reference environment is zero. When there is a good relation between the reference and natural environments, exergy analyses can be used to assess thermodynamic losses, exergy efficiencies and potential and actual environmental impacts. Extending the reference environment to the natural environment allows exergy analysis to assess and improve environmental and ecological systems.

Models for the reference environment often compromise theoretical requirements and the behavior of the natural environment. Included are 1) process-dependent models, which contain only components that partake in the process considered in a stable equilibrium composition at the natural environment temperature and pressure, 2) equilibrium and constrained-equilibrium models, which consider a mix of some subsystem of the natural environment in equilibrium or constrained-equilibrium, 3) reference-substance (natural or arbitrary) models, in which a reference substance is selected for every chemical element and assigned zero exergy, and 4) natural-environment-subsystem models, which simulate subsystems of the natural environment.

3 Exergy and Ecology

Exergy is useful in ecology and the management of ecosystems. Thermodynamics suggests ecosystems seek to maximize exergy dissipation by maximizing internal exergy storage as biomass, biodiversity and complex trophical networks. Human activity can decrease ecosystem exergy by decreasing biomass or internal complexity. Human activity converts highly-ordered self-producing ecosystems (e.g. marine estuaries, grasslands) with their rich accumulations of resources (e.g., arable soils, mineral deposits) to damaged and disordered ecosystems (e.g., eroded farmlands, depleted fisheries). Ordered ecosystems have high exergy and disordered systems low exergy. The thermodynamic laws can be interpreted in an ecosystem context (Jorgensen and Svirezhev, 2004), and explain through exergy ecosystem reactions and growth patterns, the trophic chain, reactions of ecological networks and ecosystem health. Also, exergy density and flow rate are excellent descriptors for evolution (Jorgensen, 2007a), and energy quality can be applied to nature (Salthe, 2005).

3.1 Exergy

Exergy and ecology are related (Jorgensen, 1992b, 2002a). Ecosystems have been hypothesized to develop according to increases in four attributes: ascendency, storage of exergy, ability to dissipate external gradients in exergy, and network aggradation. Exergy has been proposed as a holistic ecosystem indicator (Marques et al., 1998), and entropy as a controlling factor for ecological processes (Mauersberger, 1995). Ulanowicz et al. (2006) reconcile the attributes of ecosystems by considering exergy, information and aggradation. The exergy for organisms has been studied, including the applicability of genome size in exergy calculations (Debeljak, 2002) and the utilization of nuclear DNA in determining the exergy of biomass organisms (Fonseca et al., 2000). Some exergy-related attributes and indicators are described below.

Structural changes: Structural ecological changes are accompanied by increased exergy (Jorgensen, 1988). Exergy has been applied as goal function (Bendoricchio and Jorgensen, 1997) and in structural-dynamical modeling (Nielsen, 1990). An exergy index with ecosystem models can show that structures with the highest exergy prevail under a given set of environmental circumstances (Jorgensen et al., 2002). Exergy also is a measure of the information level of communities (Park et al., 2001).

Ecological process efficiencies: Evaluation methods were proposed for different types of exergy in living systems, considering relevant physical-chemical and physiological-ecological processes (Zhou et al., 1996), and exergy balances for animal and plant life were constructed, leading to four ecological exergy efficiency indices. Although
exergy analysis has been extended for life cycle and sustainability evaluations of industrial processes, such extensions neglect the role of ecosystems in sustaining industrial activity (Hau and Bakshi, 2004).

**Maturity:** Exergy provides a measure of ecosystem maturity, partly based on a ranking of aquatic ecosystems with several of Odum’s attributes of ecosystem maturity (Christensen, 1995). Rankings based on various ecosystem goal functions show that maturity has a negative correlation with relative ascendancy, and a strong positive correlation with system overhead, an ecosystem stability measure.

**Extremal principles, optimization and buffering capacity:** Ecological indices provide information about ecosystem behavior. Exergy has been considered as a constrained optimizing function in a structural dynamical model and tested on the phytoplankton community in a shallow lake (Nielsen, 1995). The shift in composition in a macrophyte society can be understood using exergy (Nielsen, 1997), and four types of exergy (traditional, internal, structural or modern, normalized) have been proposed as goal functions in ecosystem development and optimization. A dynamic structural model able to describe the observed changes in phytoplankton biomass and diversity was tested to determine if it behaves such that ecosystem reactions strive to maximize exergy under prevailing conditions (Jorgensen and Padasik, 1996). Extremal principles or ecological orientors or goal functions are commonly used. Exergy and ascendancy are two widely accepted goal functions, which Ray (2006) optimized in an aquatic ecosystem. Fath and Cabanas (2004) contrasted the potential as ecological goal functions of exergy and Fisher Information by comparing the indices on a ten-compartment food web model undergoing five perturbation scenarios. Furthermore, exergy has been tied to ecological constraints (Jorgensen, 1992a) and the buffering capacity of ecological systems (Jorgensen, 1982).

**Dissipation:** Dissipation (exergy destruction) involves degradation from more to less organized states, affecting the formation of structures, growth and development. Biological dissipation occurs during respiration, excretion, egestion, natural and predatory mortality and other activities. Trophic pyramids and ecological efficiencies should account for dissipation (Straskraba et al., 1999). Thermodynamic properties in an ecological model shifting from ordered to chaotic were examined for three species (phytoplankton, zooplankton, fish), as were the exergy of systems at the edge of oscillation before entering the chaotic situation (Mandal et al., 2007).

**Ecosystem health and quality:** Exergy and specific exergy of macrophytes have been examined as an integrated index to assess ecosystem health in coastal lagoons, considering 244 seaweed and seagrass species common to Mediterranean coastal lagoons and 71 sites in coastal lagoons of Southern France (Austoni et al., 2007). For a shallow eutrophic lake in China, exergy and structural exergy, as well as trophic state index, diversity index and phytoplankton buffer capacity, were considered as measures to assess ecosystem health (Xu, 1996). It is often necessary to calculate the exergy for organisms. Exergy can be estimated as the product of the biomass concentration and a weighting factor that accounts for the information carried by the organisms (Jorgensen, 2002a; Eichler and Sankoff, 2003), with weighting factors accounting for such factors as age of the organisms, number of cell types, minimum DNA content, ratio of non-coding genes to total number of genes (Jorgensen et al., 2005; Mattick, 2003). Also, exergy may provide a unified measure of water quality and pollution (Huang et al., 2007). Chemical exergy has been proposed as a objective indicator for water quality to avoid the subjectivity of conventional indicators. Water quality was examined for 72 rivers and 24 lakes (Chen and Ji, 2007).

**Biodiversity:** Ecosystems often adapt when faced with external changes, e.g. new species are take over if present ones cannot cope with changes. Using exergy as goal function provides ecosystem models with the flexibility of real ecosystems and in some ways is a translation of Darwinian selection into thermodynamics (Jorgensen, 1992c). Benthic eutrophication often gives rise to qualitative changes in marine and estuarine ecosystems, such as shifts in primary producers. Exergy has been applied in structural dynamic models of shallow lakes (Marques et al., 1997) with exergy optimised during ecosystem development so that an ecosystem self organises towards a state of an optimal configuration of exergy. Exergy constitutes a system characteristic that expresses the natural tendencies of ecosystems to evolve and a good ecological indicator of ecosystem health. The ecological significance of exergy for biodiversity, an important characteristic of ecosystem structure, was tested by examining spatial and temporal relations along an estuarine gradient of eutrophication (Marques et al., 1997). Exergy and specific exergy were suggested to be suitable alternative goal functions in ecological models and holistic ecological indicators of ecosystem integrity. Holling proposed a four-phase conceptual model of ecosystem dynamics as a guide for evaluating the impact of climate change on biodiversity, a measure
of species richness and heterogeneity, with exergy used in one approach (Hansell and Bass, 1998).

3.2 Eco-exergy
Proposed indicators for ecosystem development and health include eco-exergy, specific eco-exergy (the ratio of eco-exergy to biomass) and ecological buffer capacities (Jorgensen, 2006). Eco-exergy, a measure of a system’s deviation from chemical equilibrium, has been proposed as an ecological indicator (Jorgensen and Nielsen, 2007). Eco-exergy and exergy destruction have been used to describe aquatic ecosystem development. Respiration rate and stored eco-exergy were determined for 26 aquatic ecosystems (Jorgensen, 2007b), showing respiration rate peaks for a given type of ecosystem (Odum, 1969). Eco-exergy storage has been used to assess terrestrial ecosystems and supports the “Ecological Law of Thermodynamics” (Jorgensen et al., 2000; Jorgensen, 2002b; Jorgensen and Svirezhev, 2004).

The main differences between exergy and eco-exergy are that eco-exergy uses a changed reference state which is more useful for ecological applications, and the contribution of information exergy. When shifting from macroscopic to microscopic information storage, the exergy contribution due to information is up to three orders of magnitude greater than conventional exergy for complex living systems (Susani et al., 2006).

3.3 Emergy
Emergy, the solar energy required directly and indirectly to generate a flow or storage, has been proposed as an objective function for ecosystems. Emergy is not a state property, as it accounts for the history, time and processes that have occurred prior to the present state of the system. Self-organizing systems such as ecosystems and the biosphere can be assessed with emergy (Bastianoni and Marchetti, 1997). Emergy accounts for energy quality using a transformity factor, which is the number of solar equivalents needed to construct a given organism.

Exergy and emergy analyses both seek to represent the behavior of physical systems with cumulative energy input/output methods over space and time. The approaches also have differences, with emergy analysis focusing on energy and resource flows for ecosystems, and exergy analysis on irreversibilities and matching inputs to end-uses (Sciubba and Ulgiati, 2005). Energy-based emergy differs from exergy-based emergy (Bastianoni et al., 2007). Emergy and transformity can be written as a function of exergy alone, using partial efficiencies of processes involved in a production system starting with solar energy and ending with a product. Exergy and emergy assessments have been contrasted for ethanol production from corn, in terms of performance indicators (Sciubba and Ulgiati, 2005).

Exergy calculations for higher organisms based only on traditional thermodynamics neglect organizational level. One alternative approach is based on the thermodynamic information of genes, and another on the cost of free energy for an ecological network. The methods reflect some emergy and exergy differences, yielding results of the same order of magnitude (Jorgensen et al., 1995).

Emergy and exergy can be considered complementary objective functions, and both can describe self-organizing systems like ecosystems (Bastianoni and Marchetti, 1997). The integration of ecological extremal principles is discussed for such quantities exergy, emergy, power and ascendancy (Patten, 1995).

Some methods integrate exergy and emergy. Jorgensen et al. (2004) evaluated the emergy and exergy of genetic information and its biological carriers. The chemical exergy of genes is determined using detritus as the reference environment. The energy used to construct and maintain biological organisms is evaluated using average global emergy input to the biosphere. Emergy-exergy ratios for genes and solar transformities for biomass are determined with generalized data for populations of organisms from bacteria to large mammals. The energy required to generate the genetic information in the biosphere today has been estimated (Jorgensen et al., 2004). The relation between the emergy costs of gene maintenance and the solar transformity of biomass suggests the emergy costs of maintaining a biological carrier increases faster than the information carried as the complexity of the information carrier increases.

The emergy-exergy ratio provides the concentration of solar energy (emergy) required to maintain or create a unit of organization (exergy) (Bastianoni and Marchetti, 1997). This ratio measures how efficiently a system organizes or maintains its complexity, providing the environmental cost for the production of a unit of organization. The emergy-exergy ratio has been determined for three coastal lagoons, and observed to be lowest for the natural ecosystem and highest for the waste pond. The ratio decreases over time for the control and the waste ponds, implying these organize via natural selection. It was subsequently found that maximum emergy and maximum exergy principles in ecosystems both have practical validity and should be applied in sequence (Bastianoni et al., 2006).
4 Exergy and Environmental Impact

Relations between exergy and the environment reveal fundamental patterns affecting environment changes. Increasing exergy efficiency reduces environmental impact by reducing requirements for energy resources and emissions. But exergy also is a measure of the departure of the state of a system from that of the environment (Ayres et al., 1998; Berthiaume et al., 2001; Creyts and Carey, 1997; Gunnewiek and Rosen, 1998; Frangopoulos and von Spakovsky, 1993; Rosen and Dincer, 1997a, 1999; Dincer and Rosen, 2007; Sciubba, 1999; Wall and Gong, 2001; Baumgärtner and de Swaan Arons, 2003; Jorgensen and Svirezhev, 2004). Exergy is a measure of potential of a substance to cause change, so the exergy of an emission is a measure its potential change the environment. The exergy of an emission is zero only when it is in equilibrium with the environment. Thus exergy may be provide an effective indicator of the potential environmental impact (Dincer and Rosen, 2007).

It was some time ago suggested that exergy provides a foundation for ecologically sound planning (Tribus and McIrvine, 1971) and an air-pollution rating (Reistad, 1970). Applications of exergy in environmental impact have since increased (Ayres et al., 1998; Berthiaume et al., 2001; Creyts and Carey, 1997; Gunnewiek and Rosen, 1998; Frangopoulos and von Spakovsky, 1993; Rosen and Dincer, 1997a, 1999; Dincer and Rosen, 2007; Sciubba, 1999; Wall and Gong, 2001; Baumgärtner and de Swaan Arons, 2003; Jorgensen and Svirezhev, 2004; Connelly and Koshland, 1997, 2001a, 2001b, 2008). Exergy also can assist in allocating emissions reasonably among the outputs of multi-product systems.

4.1 Impact Indicated by Exergy

Some environmental impacts are predictable using exergy. The exergy associated with wastes (especially chemical exergy) emissions represents in some ways a potential to harm the environment. Exergy emissions can also interfere with the net input of exergy via solar radiation to the Earth, and contribute to global warming. Also, the degradation of resources found in nature destroys their exergy. For instance, combustion reduces order as does the release of a pure substance like carbon dioxide into the atmosphere and its subsequent mixing and dilution. Futhermore, environmental damage is associated with the creation of chaos or disorder, which is represented by a state of low exergy (or high entropy). A low-exergy system (e.g., carbon dioxide mixed in the atmosphere) is more disordered than one of high exergy (e.g., carbon dioxide in a tank).

The difference between the exergy values of a system in ordered and disordered states is a measure of the work required to re-order the system.

4.2 Exergy-based Environmental Methods

Several exergy-based environmental methods have evolved, sometimes by extending prior methods.

Reducing emissions via exergy efficiency: Insights provided by exergy are important in identifying efficiency improvement potential and generating sustainability policy (Hammond, 2004). Methods using exergy have been proposed for the environmental sustainability of industrial processes (Yi et al., 2004; Giannantoni et al., 2005).

Cumulative exergy consumption: The environmental impact of industrial processes can be assessed via the exergy consumption accumulated over processes. Szargut et al. (2002) suggest that the cumulative consumption of non-renewable exergy is a measure of the depletion of non-renewable natural resources. The cumulative exergy consumption approach has been used for treating emissions (Zhu et al., 2005). Cumulative exergy consumption has been extended to ecological cumulative exergy consumption to incorporate the contribution of ecosystems (Hau and Bakshi, 2004). Ecological cumulative exergy consumption accounts for the exergy consumed in ecological systems in producing natural resources. Industrial and ecological cumulative exergy consumptions in the U. S. in 1997 were determined by evaluating flows of cumulative exergy in 488 sectors (Ukidwe and Bakshi, 2007). A generalization of the approach in resource analysis and ecological evaluation has been developed based on embodied exergy, i.e. the cosmic exergy consumed in creating or sustaining a commodity or service (Chen, 2006).

Extended exergy accounting: This method facilitates assessments of a complex system by determining commodity cost based on its resource-base equivalent and includes equivalent exergy flows for labor, capital and environmental remediation (Sciubba, 2004). The method has been used to evaluate environmental externalities and suggested for forming policies (Sciubba, 2001b).

Exergy and industrial ecology: Industrial ecology, an approach to designing industrial systems that seeks improved environmental performance by balancing industrial activity and environmental stewardship and by making industrial systems behave more like ecosystems (Graedel, 1996), can incorporate exergy (Connelly and Koshland, 2001a, 2001b; Dewulf and Van Langenhove, 2002; Dincer and Rosen, 2005). Zvolinschi et al. (in press) apply exergy sustainability indicators as a tool in industrial
ecology, while Kay (2002) treats systems of varying complexity, considering applications in industrial ecology. Indicators of resource-utilization efficiency and environmental-impact potential have been developed for eco-industrial systems based on exergy and related to industrial ecology (Li et al., 2006).

**Exergy, life cycle analysis, envirornomics and ecological footprint:** Life cycle assessment (LCA), a technique for preventing pollution and improving environmental performance over an entire life cycle (ISO, 1997), can be extended to exergetic LCA (Granovskii et al., 2006, 2007). Exergetic LCA extends considers exergy flows and destructions and options for increasing exergy efficiency. The aggregate indicator ecological footprint has been extended to embodied exergy ecological footprint, which shows the ecological overshoot of ecological systems (Chen and Chen, 2007). Environomics simultaneously accounts for energy, exergy, economic and environmental factors in energy systems (Frangopoulos and von Spakovsky, 1993).

**5 Extensions to Economics**

Links between exergy and environment and ecology can be extended to economics, with exergy's potential as an environmental indicator incorporated in exergy-based economic assessments (Edgerton, 1982). By extending exergy and economics to account for environmental effects, techniques can developed that minimize life cycle costs while reducing environmental effects. Ayres (1998) links economics and the second law via eco-thermodynamics and Sciubba (2005) proposes exergoeconomics as a thermodynamic foundation for rational resource use.

Tonon et al. (2006) propose a method based on energy, exergy, economic and environmental factors to assess possible areas of improvement. A method for performance evaluation under maximum ecological and maximum economic conditions is proposed, where the ecological function is represented by the power output divided by the entropy generation rate and the economic function by the power output divided by the total cost (Tyagi et al., 2007). A thermoeconomic method to increase the efficient use of exergy resources based on a carbon exergy tax is proposed (Santarelli, 2004). To obtain exergy-based indicators of sustainable development, Ferrari et al. (2001) integrate thermodynamics and economics. Exergy also has been applied to the economy to develop a model for sustainable development at the macro-economic level by combining resource depletion with pollution to reduce degradation losses (Honkasalo, 1998).

Sciubba (2001a) extends exergy accounting and thermoeconomics with environmental factors to improve analysis and design. Sciubba (2003, 2004) also proposes extended exergy accounting as a cost analysis method using a resource-based quantifier (extended exergy). Environmental remediation costs are considered by determining the equivalent cumulative exergy expenditure to achieve zero impact. Lazzaretto and Toffolo (2004) show how designs can be optimized using objectives relating to energy, exergy, economics and the environment.

Exergy-based economics has been linked to ecology, and an ecological perspective of economic development and environmental protection described (Rees, 2003). Ecological economics interprets the environment-economy relation in terms of exergy, viewing economic activity as a dissipative (exergy consuming) process. Rees notes that the ascendance of humanity has consistently been accompanied by an accelerating rate of ecological degradation.

**6 Conclusions**

Exergy exhibits many useful relations with ecology and the environment. The exergy-based relations provide a foundation for exergy-based ecological and environmental methods, which are useful for analysis, comparison and improvement. The methods combine thermodynamics with ecology and environmental concepts and can be used to achieve advantageous designs. It appears that environmentally successful systems may be configured so as to balance appropriately exergy-based economic and environmental and ecological factors. It is emphasized that analogous relations between energy and ecology and the environment in general are not useful and sometimes are misleading.

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