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Entropy, economics, and policy

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- **Was ist nötig, um deren „Abwehrkräfte“ zu steigern?**

Die Hauptkompetenzen liegen in den Bereichen: Arbeitswissenschaft, Technikfolgenabschätzung und Technikbewertung, Managementlehre, Unweltsoziologie und Umweltpolitik.

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(Arnim von Gleich, Hans Dieter Hellige, Ulrich Dolata)

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(Hellmuth Lange, Ines Weller)

Entropy, Economics, and Policy

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Abstract

The laws of thermodynamics constrain transformation of materials and energy, and thus have implications for material and energy use in the economy, for environmental impact, and for policy. This paper provides an overview over the applications of concepts from thermodynamics in economics at the level of individual processes and explores potential constraints at larger system levels – the economy as a whole and the ecosystems within which economies are embedded. Specific emphasis is placed on the ways in which insights from thermodynamics are used to inform economic and policy decision making.

Biography

Dr. Matthias Ruth is visiting professor at artec, Universität Bremen, and Roy F. Weston Chair in Natural Economics, Director of the Center for Integrative Environmental Research at the Division of Research, Director of the Environmental Policy Program at the School of Public Policy, and Co-Director of the Engineering and Public Policy Program at the University of Maryland. His research focuses on dynamic modeling of natural resource use, industrial and infrastructure systems analysis, and environmental economics and policy. His theoretical work heavily draws on concepts from engineering, economics and ecology, while his applied research utilizes methods of non-linear dynamic modeling. Professor Ruth has published 9 books and over 100 papers and book chapters in the scientific literature. He collaborates extensively with scientists and policy makers in the USA, Canada, Europe, Oceania, Asia and Africa.

> *If Thought is capable of being classed with Electricity, or Will with chemical affinity, as a mode of motion, it seems necessary to fall at once under the second law of thermodynamics as one of the energies which most easily degrades itself, and, if not carefully guarded, returns bodily to the cheaper form called Heat. Of all possible theories, this is likely to prove the most fatal to Professors of History.*
> Henry Brooks Adams (1838–1918), U.S. historian.
> The Degradation of the Democratic Dogma, p. 195.

1. Introduction

Modern, mainstream economics is as much a product of social and political history as it is of scientific method. The decline of centralized power in the late medieval ages, held previously by kings, feudal lords, bishops or priests, increasingly provided opportunities for individuals and their communities to determine their fate. As the roles and responsibilities of individuals were redefined and as decision making became decentralized, concerns were raised whether a society, driven by individuals and their self-interests, could and would be able to reach some stable outcome (Smith 1776, Brems 1986).

The technological innovations of the agricultural and industrial revolutions further fueled, and were driven by, economic growth and social change. Related rapid changes occurred in the physical, engineering and health sciences, all of which influenced economists' approaches to understand the rapidly increasing complexity of society (Martinez-Alier and Schlupmann 1991). By the end of the 19th century, highly abstract, mathematical descriptions of economic activity were available with natural-law-like character, to be applied anywhere and anytime to gain insights into the interactions of producers and consumers. Objective functions for households and firms were postulated, and, on the basis of those postulates, conditions were derived under which the decisions of all actors in the economy came to a general equilibrium – a state at which profits of firms are maximized, consumers reached a maximum level of satisfaction, and all markets cleared, given the resource endowments and technologies available to society (Malinvaud 1972, Mas-Colell 1985). Where conditions for optimality are not met, interventions are sought to get closer to, or actually achieve economic equilibrium. The main instruments for interventions are changes in relative prices of goods and services, for example by imposing taxes, or changes in the forms of markets themselves, such as by deregulating monopolies or providing incentives for increased competition (Katz and Rose 2002).

One of the most frequently mentioned definitions of economics, stemming back to the 19th century, is that of a science which seeks to identify the optimal allocation of scarce resources to meet the needs of humans. Initially, labor and capital were considered as scarce, but subsequent expansions began to include natural resources as well as the environment's waste assimilation and absorption capacities. The notion of equilibrium and stability was contrasted by that of a "steady state" in which the economy develops within the constraints given by a finite resource endowment and near-constant influx of energy into and out of the earth system (Daly 1973, 1991).

The broadening of boundaries around the economy to explicitly include resource and waste streams has also prompted closer attention to ecological processes. Instead of separate from its environment, the economy increasingly is considered a subsystem of the ecosystem, with each, and the relation between them, always changing (Costanza and Wainger 1991).

The early fascination of economists with state-of-the-art mathematics and physics has imparted undeniable influence over the development of economic theory, often prompting a reference to economics as the physics of social sciences (e.g. Freeman and Perez 1988, Sarkar 1998). With the stature that comes from a high degree of scientific formalism, the role of economists in providing decision support has increased. Some have gone so far as to refer to them as the new high priests of society (Nelson 2001), offering advice, making predictions, and consorting with the secular world much like the priests of the medieval periods have done.

As mathematics and physics advanced, and as the roles of natural resources and the environment for economic activity surfaced on the radar of economic analysis, new concepts and tools were imported from physics to advance economic theory. Similarly, as the economy has become redefined as part of the ecosystem and as ecosystem change has been intricately linked to economic change, notions of evolution and co-evolution have increasingly come to the fore (Norgaard 1994).

None of these recent changes, though, have fundamentally altered mainstream economics, but have rather taken place at the fringes of the discipline, largely ignored or disregarded by the majority (Cleveland and Ruth 1997). Those, in contrast, who have argued for a revision of mainstream economics, are gaining in numbers and influence. Their critique of the mainstream is founded, in part, on the notion that disregard of recent advancements in physics and biology renders answers from mainstream economics to the challenges of modern society irrelevant or misleading. Proponents of this "new" economics suggest, as a correlate, that investment and policy decision making processes need to be updated with the insights from modern physics and biology, rather than based on the economic models crafted after 19th and 20th century natural sciences (see, e.g., Faber et a. 1987, Funtowizc et al. 1998, Faber at al. 1996).

This paper, though not intended to provide a history of economic thought, traces some of the conceptual changes in economic modeling to developments in physics, particularly to thermodynamics. Since thermodynamics has also increasingly influenced biology and ecology, and insights from the latter, in turn, are shaping modern analysis of complex human-environment interactions, special attention is also given to the relation of economics to biology. While tracing some of the relations among economics, ecology and thermodynamics, the paper lays open important ways in which the mindsets behind economic analysis are shaping policy making, and new ways in which policy may develop, given recent advancements at the interface of economics, ecology and thermodynamics. Here, notions of stakeholder involvement, adaptive and anticipatory management, and planning in the light of uncertainty and surprise surface in contrast to expert-driven economic advice grounded on partial or general equilibrium models.

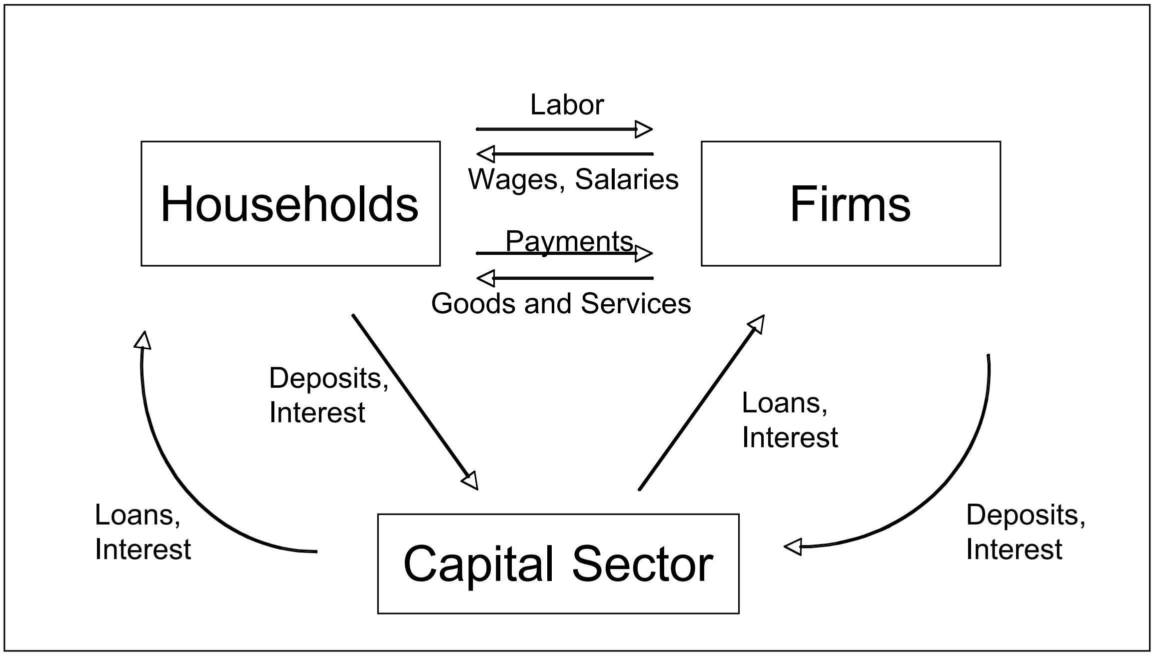
The structure of this paper closely follows this line of argument. In the next section, I briefly review the influences of equilibrium thermodynamics on economics and biology. Section 3 outlines the basic tenets of non-equilibrium analysis and section 4 addresses insights for investment and policy making. Section 5 closes the paper with a brief summary and conclusions.

2. Mass and Energy Flows Through the Economy

2.1 Mass and Energy Balances

Traditional economic analysis concentrates on the exchange of wealth among the members of an economy, focusing on the role of consumer preferences, technologies, and capital endowments for the existence and stability of market equilibria. The underlying world view is one of circular, monetary flows among the members of the economy (Figure 1), a kind of perpetual motion machine in which purchases of goods and services result in profits for firms which can be used to purchase labor and other inputs into the production process. Savings of households, for example, provide means for investment in capacity and productivity of firms, which in turn requires inputs and leads to outputs available to consumers (Heilbroner and Thorow 1982). Resource flows into the economy and waste flows from it, are considered to the extent that they have monetary values associated with them, for example for their purchase as inputs into production by firms or for the compensation to households for loss of welfare from harm being done onto them. Where those monetary flows do not exist, yet the physical flows impact the economy, internalization of externalities may be achieved, *a posteriori*, by establishing markets for those flows, as has been attempted, e.g. for water allocation or sulfur emissions (Baumol et al. 1994).

Figure 1. Basic Circular Flow Model of the Economy, with Capital Accumulation (modified from Heilbroner and Thorow 1982).



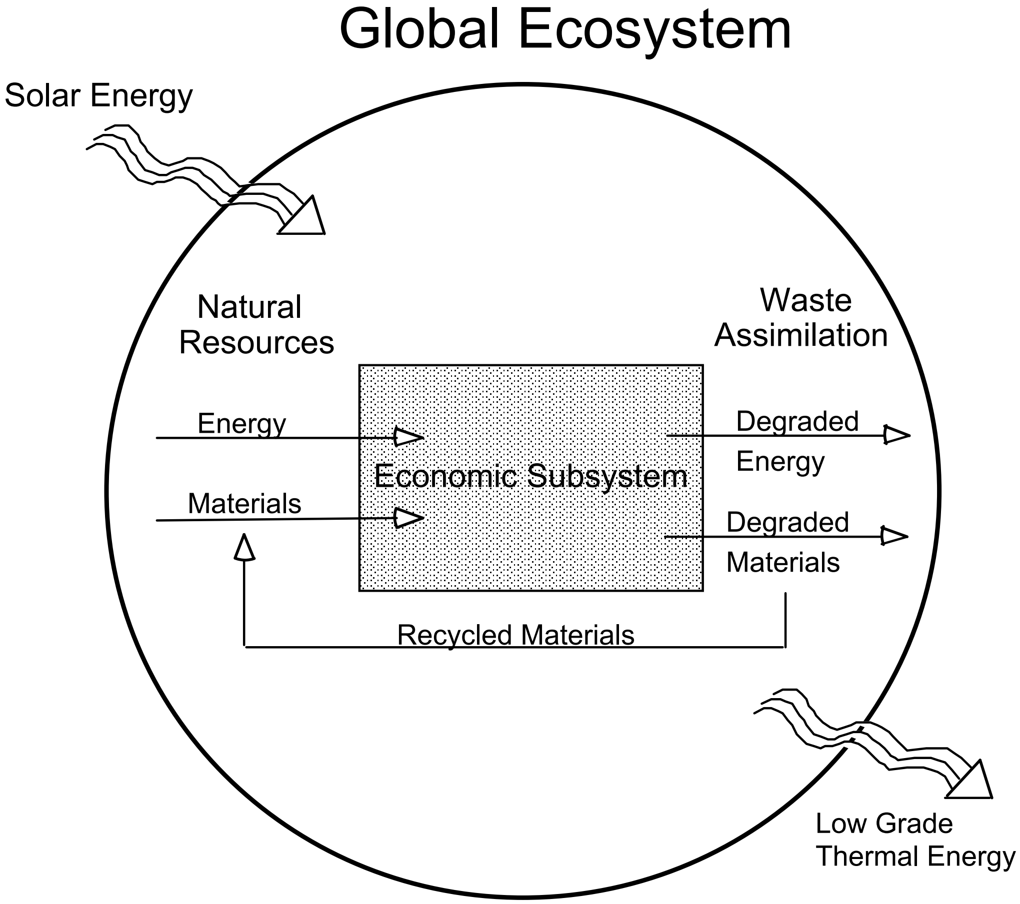
Among the earliest and most influential efforts to begin extending the monetary-flow model of economics to account for material and energy flow has been Georgescu-Roegen's work on the biophysical basis of the economic process (1971, 1976, 1977, 1986). His efforts occurred independently of, and at the same time as Boulding's (1966) celebrated demonstration of the environmental implications of the mass-balance principle, Odum's (1971) energy flow analysis, Ayres and Kneese's (1969), Converse's (1971), Victor's (1972), and d'Arge and Kogiku's (1973) materials balance approach, and Hannon's (1973, 1975) application of input-output techniques to the analysis of energy use in ecological and economic systems.

Much of the attention surrounding the law of conservation of mass is paid to limits imposed by the law on the growth of economic systems. In contrast, little attention has been paid by these early studies to the fact that the generation of waste products by the economy and their release into the environment leads to environmental change that necessitates that production processes change over time. Turning to that issue, Perrings (1987) developed a model of an economy that is constrained by the law of conservation of mass and exhibits the evolution of production processes in response to changes in the environment. His model contrasts the model by Ayres and Kneese (1969) and its successors that attempt to examine the implications of the conservation of mass for general economic equilibrium within a static allocative framework. Perrings' model stresses the necessity for an economic system to respond to disequilibria that are caused by processes in the environment that are not reflected in, or controllable through, the price system.

2.2 Economy and Second Law

The concept of the economy as a physical system subject to the laws of physics can be illustrated by defining the system boundary to encompass producers and consumers of goods and services and the intermediate inputs and final output. The environment, in turn, can be defined as the system containing all natural resources and the sinks that receive all waste (Figure 2). Thus, the combined system consisting of the economy and the environment is defined as a closed system with no materials crossing the system boundary. Energy stocks are depleted for the purpose of changing the thermodynamic state of materials from their natural state to one that is more highly valued by humans. Since materials are conserved rather than "consumed", the analysis traditionally focused on the use of energy to effect the desired changes in the state of material resources and the associated build up of capital in the economy (Faber et al 1987, 1990).

Figure 2. The economy is an open subsystem of the larger closed environmental system. The economic process is sustained by the irreversible, unidirectional flow of low entropy energy and materials from the environment, through the economic system, and back to the environment in the form of high entropy, unavailable energy and materials (modified from Hall et al., 1986).



In addition to the build-up of material endowments with desirable thermodynamic properties, humans accumulate knowledge about the processes (technology) for effecting desired changes in the state of materials. Thus, high-quality energy is degraded to produce work which, in turn, produces low-entropy (highly-ordered) configurations of molecules (goods, capital plant and equipment), and information (services, technological know-how).

2.3 Economy and Information

The relation between energy and information is fundamental in thermodynamics, having served as the basis for Szilard's exorcism of Maxwell's demon (1929), confirming the validity of the second law of thermodynamics. Shannon (1948), Shannon and Weaver (1949) and Wiener (1948) were the first to explore rigorously the relationship between information and order in the context of communication theory. Information was defined as a measure of uncertainty that caused an adjustment in probabilities assigned to a set of answers to a given question. In quantifying the uncertainty introduced by random background noise in a communications signal, and calling it entropy, they set the stage for Brillouin (1964) to identify negative entropy with knowledge. Evans (1969) and Tribus and McIrvine (1971) formalized the connection between Shannon's work and thermodynamic information, in which entropy differences distinguish a system from its reference environment. Stressing the nonequilibrium character of systems that are distinguishable from their reference environment, Berg (1988) uses information as a measure of the order of a product.

Going a step further, Spreng (1988) ranks economic activities by the relative importance of their output, measured by information, and compares over time various production processes by their efficiency. The choice among alternative technologies used to "speed up the pace of life" or conserve valuable resources must be made by society, informed by the physical and ecological processes that are associated with economic activity.

Material composition and thermodynamic state are in fact what distinguishes one product from others and from its surroundings. Yet, from a physical perspective a product has no intrinsic value, although it is possible to quantify the amount of energy required to change the thermodynamic state of the input materials from their initial to a final state. The value of 'goods' (materials in highly-valued thermodynamic states) is determined by humans based on sensory inputs received by the brain. For example, warm air molecules in a heated room produce valuable sensory inputs, and humans minimize the cost of those inputs by selecting optimal combinations of furnaces, fuels, insulating materials and clothing. Similarly, other goods and services can be modeled physically as materials in particular thermodynamic states that produce audio and visual sensations or smells and tastes that human "consumers" value.

This physically-based model aids in the valuation of goods and services by providing a more quantitative foundation for utility theory, and a broader framework for analyzing technological innovation. By focusing on the fact that the net output of the economic system is information, it illustrates the potential for materials conservation (e.g. artificial sweetener technology, solid state electronics). Since the theoretical minimum energy required to produce a bit of information is so small (Szilard 1929), the potential for energy-conserving technological change is correspondingly large. For example, a comparison of the energy cost of information handling processes using character record technology such as an electric typewriter (1.4 Joule/bit) with digital record technologies such as computer output (0.3 Joule/bit) reveals significant differences (Tribus and McIrvine 1971), with both being significantly larger than the theoretical minimum thermodynamic entropy change associated with one bit of information ($4.11\ 10^{-21}$ Joule at ambient temperature) (calculated from Szilard 1929).

An information-based approach to resource use was chosen in a theoretical analysis by Ayres and Miller (1980) and later applied to the U.S. energy sector by Ayres (1988). Natural resources, labor, physical capital and knowledge are all treated as forms of information and, within limits, mutually substitutable. Accumulation of knowledge and its embodiment in physical capital and labor skills leads to changes in the processing efficiency of economic system, and thus, to decreases in the release of waste materials and heat into the environment. Yet, little attention was given to the fate of waste products in the environment and the connection between waste generation and information as a measure describing products, technologies and technical change.

With the theoretical background provided by studies on thermodynamic information and applications to energy and material use in economic processes, Ruth (1993) formulated a model of a simple economic system in which all production functions and consumption processes were explicitly constrained by the laws of conservation of mass and energy. Ruth analyzed quantitatively the use of high-quality energy inputs for increasing the order of materials inside the economic system boundary. In addition, production functions changed as learning occurred, asymptotically approaching the theoretical maximum levels of materials and energy efficiency. The mass of the system remained constant. The net effect of energy input to the system was to increase the order of the materials (e.g. goods) and to change the state of knowledge (technology).

The same physically-based analysis may be applied to the entire ecosystem of which economic systems are a subset. Incident solar energy is captured and concentrated by plants and animals, and used to perform the work required to maintain materials in low-entropy forms that provide the infrastructure for survival. Materials are conserved in the system and tend, in the absence of energy channeled through living organisms, towards a less-ordered (high-entropy) state.

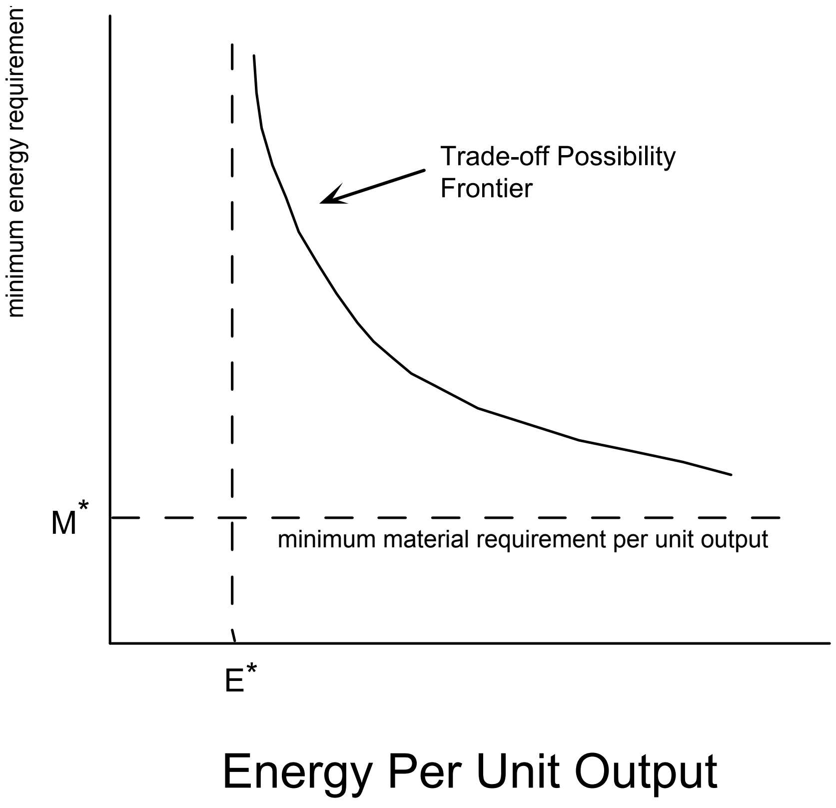
2.4 A Brief Conceptual Assessment of Equilibrium Thermodynamics in Economics

Significant headway has been made in the last few decades to provide a biopysical foundation for economics, and to interpret economic processes from the perspective of thermodynamics. The studies cited above, and similar efforts, may be grouped into two broad categories – the ones which attempt to establish formal mathematical models of the economy in analogy to thermodynamics, and those directly applying thermodynamic laws to economic processes, such as the use of materials and energy for the concentration of materials (Martinez-Alier 1997, Baumgärtner 2004). Comparable observations can be made for modern ecology, with formal model development in analogy to thermodynamics (e.g. Jørgensen and Svirezhev 2004) and straight-up applications of thermodynamic laws to individual ecosystem processes (e.g. Luvall and Holbo 1991).

Motivations for the development of economic theory in analogy to thermodynamics lies in the power of establishing isomorphic theories that enable transfer of insights from one area of scientific inquiry to another. However, isomorphism of formal structures between economic theory and thermodynamics, does not imply that economic theory complies with thermodynamic laws. For example, as Sousa beautifully pointed out (2006a), "[t]he formal equilibrium considered for the consumer problem is not the thermodynamic equilibrium of the consumer. The thermodynamic equilibrium of the consumer would be a dead consumer."

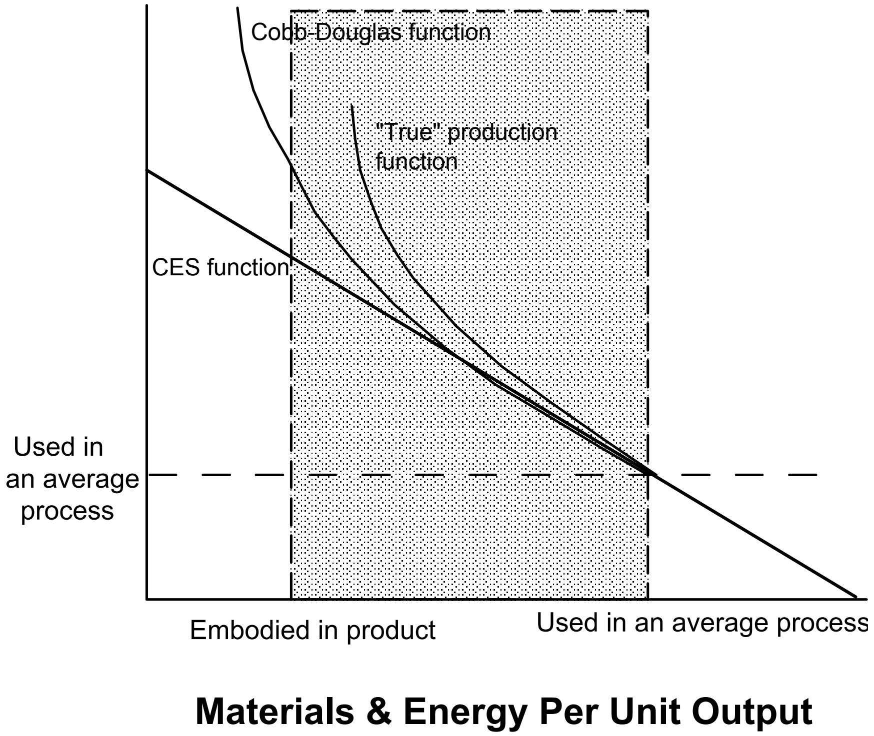
While analogy-based theory-building may help economize on theory-building itself, the studies directly applying thermodynamics to economic processes gain power over traditional economic approaches because they explicitly identify and account for thermodynamic limits on the transformation of materials and energy. As an example, the production function represented in Figure 3 illustrates these constraints. The minimum material and energy inputs required to produce a desired output are defined by M^* and E^*, respectively. The function which describes the substitution possibilities between M and E is bounded by these lower limits. This approach has been used in empirical analyses of material and energy use in individual processes such as copper extraction (Ruth, 1995a, Gössling-Reisemann 2006), and copper and aluminum processing (Ruth 1995b).

Figure 3. Trade-off possibility frontier for energy and material inputs per unit of output (modified from Ruth, 1993).



But what about the substitution possibilities at the level of an economy? The thermodynamic analysis described in Figure 4 is based on mass, energy and exergy balances of individual production processes. It requires detailed information on material and energy flows and as a result is difficult to accurately apply at the level of an entire economy. Many different forms of energy and materials are used as raw materials. Materials in particular are extremely heterogeneous at a macro level because humans use all 92 naturally occurring elements. Capital itself exists in myriad forms at larger scales, making it difficult to generalize about the material and energy requirements of producing and maintaining capital. By the same token, the abilities of workers to perform processes are inherently linked to their social, cultural and educational backgrounds. It was this heterogeneity of funds and flows—machines, labor, materials, energy, knowledge—that prompted their aggregation in monetary terms and further masked the physical realities of the production process.

Figure 4. Possibilities for substitution between human and natural capital implied by different production functions. Due to the complementarity between human and natural capital, the substitutions are limited to the shaded area (modified from Ayres and Nair, 1984).



Despite these problems, the complementarity between human-made and natural capital enables us to distinguish production functions that are consistent with physical reality from those that are not (Figure 4). In certain applications or interpretations, widely used models such as the Cobb-Douglas or constant elasticity of substitution (CES) production functions (Shaphard 1981) embody the physically impossible assumption that a given output can be maintained as energy or material inputs vanish as long as human-made capital can be increased sufficiently. In reality, the substitution possibilities are limited to the quantity of energy and materials embodied in final goods and in capital itself (Dasgupta and Heal 1979, Meshkov and Berry 1979, Ayres and Nair 1984, Perrings, 1987, Ruth 1993, 1995c).

3. Non-equilibrium Thermodynamics and the Complexity of Economy-Environment Interactions

3.1 Resource Use and Pollution as Non-equilibrium Processes

Most of the studies that use thermodynamics for economic analysis have been based on equilibrium thermodynamics, though clearly, non-equilibrium thermodynamics would be more appropriate because the economy and the ecosystem, within which it is embedded, are thermodynamically open systems kept out of equilibrium by mass and energy flows across their system boundaries (Reiss 1994, Sousa 2006b). As with equilibrium thermodynamics, the import of non-equilibrium thermodynamics strives for applications to specific processes or occurs in the form of analogies. However, actually applications are limited in number and scope, and analogies are more structural than formal. This section of the paper addresses both kinds of attempts.

Assuming an open system is not in, bit close to, its equilibrium position, the entropy generated inside the system by naturally occurring processes per unit of time, d_iS/dt, is the sum of the products of the rates J_k and the corresponding n forces X_k (k=1:n) such that

$$P = \frac{d_iS}{dt} = \sum_{k=1}^{n} J_kX_k > 0 \tag{1}$$

The rates J_k may characterize, for example, heat flow across finite temperature boundaries, diffusion, or inelastic deformation, accompanied by generalized forces X_k such as affinities and gradients of temperatures or chemical potentials (Prigogine 1980). In the steady state, the entropy production inside the open system must be accompanied by an outflow of entropy into the system's surroundings. Systems approaching the steady state are characterized by a decrease in entropy production, i.e. $dP/dt < 0$.

Equation 1 holds only close to a local equilibrium. Far from equilibrium, it is typically not appropriate to assume the linearity suggested by equation (1). There is considerable debate, in how far the "close-to-equilibrium" assumption can be maintained for the analysis of production and consumption processes in living systems, engineering systems or economies. If the corresponding systems are far from equilibrium, using Equation (1) to assess system change may be circumspect at best.

In the nonlinear realm, systems can be characterized by a generalized potential, the excess entropy production. Excess entropy production is defined as

$$P_E = \sum_{k}^{m} \delta J_k \, \delta X_k \tag{2}$$

with δJ_k and δX_k as deviations from the values J_k and X_k at the steady state. Unlike for systems in, or close to, equilibrium the sign of P_E is generally not well defined. However, close to equilibrium the sign of P_E is equal to that of P (Glansdorff and Prigogine 1971).

Calculations of excess entropy production show decreases in P_E in open systems moving towards steady state. For example, an increase in temperature gradients in a far-from-equilibrium system may trigger increasingly complex structures, as Bénard's experiments clearly demonstrate (Prigogine 1980). The evolution towards these structures is typically not smooth but accompanied by discontinuities and instabilities. In the critical transition point between stability and instability, a more complex structure emerges and $P_E = 0$ (Glansdorff and Prigogine 1971). Excess entropy production can therefore serve as a measure of changes in the structure and stability of a system. However, its applicability to real, living systems and especially to economic systems is severely limited by the lack of data sufficient for meaningful calculations (Ruth 1995).

Much movement, however, can be observed for the use – by analogy – of general insights that non-equilibrium thermodynamics provides for the study of complex systems. The concepts of non-linearity, complexity, chaos, catastrophe, criticality, resilience and adaptation all deeply resonate with scientists and practitioners interested in re-evaluating and re-shaping human-environment interaction. The following section briefly addresses these concepts, before I explore their value as guiding principles in investment and policy decision support.

3.2 Complex Economy-Environment Interactions

From a systems perspective, both the economy and the ecosystem, within which the economy is embedded, can be understood in terms of non-linear, dynamic, often time-lagged processes that connect individual system components. Some of these processes are self-reinforcing, for example when environmental impacts on the economy reduces its ability to cope with such impacts. Others are counter-acting, for example when increases in stocks of renewable resources prompt increased harvest, which in turn diminishes the stocks. The presence of both such positive and negative feedback processes, and the fact their strengths change through time, add to the challenge when trying to understand overall system behavior in space and time.

The connections among system components often take place across different system hierarchies. For example, employees in firms, firms in industries and industries in economies, or individual organisms within populations and populations within ecosystems interact with each other through exchanges of materials, energy and information. As a consequence, analyses often need to take into account specifically the processes at system hierarchies above and below those of actual interest, lest important influences and impacts are neglected.

Since the economy interacts with its environment, nonlinear, time-lagged feedback processes occur not only within and among the hierarchies of each of the system but connect to the outside as well. Discovery and use of fossil fuels stimulated economic activity and triggered the large-scale deployment not only of combustion technology around the world, but also of changes in society at large. The extractive processes themselves changed local ecosystems, as has been painfully become apparent for oil and gas extraction in Louisiana or coal extraction in China, for example. Emissions of greenhouse gases from combustion, in turn, impact ecosystems from the local to global scales. Recognizing not only the adverse impacts from fossil fuel use but also the opportunities that may come from the developments of alternatives, far-reaching technological, behavioral, and institutional changes are sought which may redefine modern society.

Taking a long view and drawing on the insights generated in systems theory, one may interpret such developments from an entropic perspective. For example, Hannon et al. (1993) and others have hypothesized that ecosystems evolve towards climax states that are the most massive and highly-ordered structures that can be maintained on the limited energy budget. As these systems evolve, knowledge accumulates in the genetic material that serves as blueprints for material and energy transforming processes. Similarly, the increasingly rapid entropy-generating activities of fossil fuel use through ever more sophisticated pathways developed in modern societies may be perceived as increasingly effective means to degrade existing environmental gradients. The selforganization of the globalizing industrial system shows similarities to the build-up of structure and organization in physical and biological systems and like those may experience critical thresholds that will lead to reorganization (Bak 1996). Given the complexity of the system, it is neither not knowable where those thresholds are, when exactly they may be encountered, and what the subsequent developments paths look like. Yet, if past system performance is a guide, new build-up of structures is likely to occur.

Selforganized criticality is wrought with fundamental uncertainties. A challenge to decision makers in industry and policy, for example, will be to identify actions and promote the development of mechanisms that foster resilience of the individual systems with which they deal, and the overall sustainability of the larger system within which those are embedded. Adaptive and anticipatory management have been promoted as responses to uncertain, ever-changing relations between society and its environment.

4. Adaptive and Anticipatory Management

The complexity of economy-environment interactions is not simply a result of the connections of a myriad of system components, but fundamentally and inherently related to our ability to comprehend and explain them. One disciplinary perspective, be it economic, engineering, biological or other, will not be sufficient to encompass the relevant system features.

To illustrate the need for multiple perspectives, consider the role of nuclear power in energy supply. A physical description, though highly relevant, only provides basic insights into the processes of nuclear fission or fusion. Engineering perspectives offer technical descriptions of resource extraction, power generation, or waste disposal. Economics helps quantify opportunity costs of alternatives. Biology helps trace environmental impacts, medicine describes human health implications. But without, for example, an understanding of psychology, sociology, history, ethics and law, any assessment of the opportunities for and constraints on nuclear power as an energy source are incomplete at best. The complexity of the issue comes not only from the many possible interactions at the physical and technological levels, but also from the many pathways through which their ramifications permeate environmental, economic and social systems. The possibility for bifurcations extend in multiple dimensions when moving away from simple physical descriptions. Likewise, more degrees of freedom exist to promote selforganization and resilience outside the simply physical world.

Major challenges to modern society and to the scientific enterprise facing complex economy-environment interactions persist. Institutions and mechanisms have developed to reward discipline-specific advancement. Universities and science foundations still struggle with assessments and quality control of interdisciplinary research and education. A parallel culture of investment and policy advisors feeds off discipline-specific knowledge, based on the reduction of complexities. No comparable social processes are in place to help embrace complexity. Deliberative democracy remains more of an ideal than a lived reality. Among the few pragmatic approaches are adaptive and anticipatory management, which have found widespread recognition in the field of ecosystem management and are slowly permeating investment and policy making.

The notion of adaptive management has been spawned by the recognition that since boundary constraints for management continuously change, no one action will ever necessarily achieve desired long-term results (Holling 1978, Gunderson et al. 1995, Ruth 2006). Impacts of decision making need to be observed and fed back to inform and influence subsequent rounds of assessment and decision making, *ad infinitum*. The larger the time lags between system intervention and system response, the more important it will be to base interventions. Notable examples are investments in infrastructure, which are often lumpy and irreversibly alter the economic, social and biophysical environment. The time between investment, observation of impacts and revision/refinement is often too large to meaningfully allow for adaptation, making anticipation and identification of robust strategies – strategies that are desirable under a wide range of alternative futures – all the more important.

A goal of adaptive and anticipatory management is not only a continuously fine-tuned approach to problem solving but, as a pre-requisite, a continuously improved understanding and appreciation of the system dynamics, as the system itself evolves. One way to improve that knowledge is through the use of formal, transparent computer models that embed as much of the relevant system attributes as possible, and to then use those models in a structured and iterative discourse with stakeholders.

Stakeholders from academia, policy, industry, nonprofit organizations, the public and many other walks of life may make valuable contributions to the modeling process, and their inclusion in that process can set a stage for constructive dialog about alternative investment and policy decisions and actions. That dialog can be an essential ingredient for anticipatory management of socioeconomic systems in light of many complex settings in which decisions need to be made, in which the stakes are high, and uncertainties abound.

While efforts are increasing the diversity of perspectives – from different academic disciplines to a wide range of stakeholder inputs – in formal assessments of economy-environment relations, the resulting models often are fairly basic with respect to the material and energy flows they capture, the interlinkages among system components, and the richness of dynamic processes overall. While true, in spirit, to the insights from thermodynamics and complexity, very little substantive import of physical laws can be found in these models. Much room exists to offer a substantive basis.

5. Summary and Conclusions

Over the last five decades, two main strands of research have developed to provide a physical basis and interpretation of socioeconomic development in its relation to environmental change. One of these strands applies physical concepts and laws to quantify material and energy use from a thermodynamic perspective. Given the difficulties to do so, analyses typically limited themselves to individual processes or process chains. Examples include efforts to quantify exergetic requirements for the extraction and refinement of ores, or the entropic nature of human consumptive processes. The second strand of research has been guided by analogies and systems-theoretic insights and tended to be largely conceptual and qualitative, though not necessarily less appealing as guides to decision making than their quantitative, process-specific counterparts. Examples include interpretations of economic and social change from the perspective of entropy theory, chaos theory, catastrophe theory, or selforganized criticality.

Together, these two strands of research have nicely contributed to the ongoing sustainability debate by juxtaposing hitherto standard static, linear, equilibrium-focused analyses, as they are common, for example, in traditional economics, with the notion of non-linear dynamics in a world where irreversibilities dominate, and adaptation and anticipation are key to success. Rather than dealing with isolated systems for which experts provide probabilistic forecasts as inputs into planning and management, the post-modern approach recognizes openness and hierarchies as essential system features that contribute to complexity, cause surprise, and require scenario-based exploration of the impacts of alternative system interventions. The institutional implications of these developments are clear – the basis for decision making needs to be shifted from limited expert advice to diverse, consensus-based approaches that promote responsibility and stewardship. As the sciences provide quantified and structural insights into changing human-environment relations, institutional innovation will need to explore alternative means by which to translate those insights into action. Here may also lie the frontier of 21st century environmentalism.

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