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“Energy and Resource Flow Analysis” by Jonathan M. Harris

The structure of ecological economic theory, as we have outlined it above, clearly implies a more central role for the analysis of energy and biophysical resource use than does standard economics. The articles in this section go into greater depth concerning the implications of this perspective for analysis and policy. Some of the discussion here is still on a theoretical level, but there are also significant efforts to develop specific techniques appropriate to this new perspective. These offer insights into economic theory, data analysis, and policy formulation which are significantly different from those derived from the neoclassical model. We can also note here that as ecological economists attempt to come to grips with the real-world implications of their theory, differences of opinion and of interpretation within the field become more pronounced.

The fountainhead of energy and resource flow analysis is found in the work of Nicholas Georgescu-Roegen. As we have already seen, there is considerable controversy over the value and implications of his theories. The most detailed exposition of his thought is in his 1971 book The Entropy Law and the Economic Problem, but his short article on "The Entropy Law and the Economic Problem" is more accessible to most readers. Here is set forth the basic view of the economic system as an "open" subset of a larger biophysical system, with matter and energy crossing the boundary into the economic system in a low-entropy state, and returning in a high-entropy state. This unidirectional flow differs fundamentally from anything in standard economic theory, which sees the economy as a closed system balanced by internal market equilibrium. From this basic analysis Georgescu-Roegen draws some lessons of sweeping importance. One is that the production process necessarily results in an *entropy deficit,* a draw-down of "wealth" in terms of available energy and resources. Another is the fundamental distinction between the *stock* of terrestrial resources, analogous to capital, and the *flow* of solar energy, analogous to income. The difference between living on income and living on capital is clear, but prior to Georgescu-Roegen's work it had rarely been applied to energy and resource economics.

Georgescu-Roegen uses the inexorable logic of entropy to define the limits of economic activity. No industrial system can continue indefinitely drawing down terrestrial stocks of low entropy. (Note that this argument is not framed simply in terms of quantities of available resource reserves but takes in the logic of rising costs and increasing environmental damages as production proceeds.) Also, there are strict limits to what can be achieved through technological progress or resource recycling. Technological optimism must be subordinated to the entropy law; what Georgescu-Roegen calls "entropy bootlegging" is as impossible as perpetual motion. Even a steady-state, non-growing economy will progressively degrade its terrestrial resource base. Hence the unique importance of solar energy - it is the only truly "free" good, but a difficult one to utilize well due to its diffuse nature.

What are some of the practical implications of the entropy analysis? We must remember that Georgescu-Roegen's original work was published prior to the wave of awareness generated by environmental problems that have drawn wide public attention in the last twenty years. His work can certainly be regarded as prescient in providing a theoretical framework to explain concerns about both resource adequacy and global environmental pollution. But how can it be applied to economic analysis? Some economists have argued in response that while the entropy limits posited by Georgescu-Roegen must undoubtedly apply to economic activity in the long term, their practical impact is so far off as to be irrelevant to current economic analysis. In this view, the entropy law provides a nice metaphor for an over-consuming, over-polluting society, but nothing more. Policy issues of resource management and pollution control will not be subject to binding entropy constraints for centuries, according to many leading economists (see for example Robert Solow's 1974 article on "The Economics of Resources or the Resources of Economists"[1]).

The energy and resource flow analyses in this section are predominantly oriented to proving this critique wrong by developing practical applications of analyses of energy and resource flows. (Only the article by Young endorses the neoclassical skepticism about the relevance of entropy theory.) Some respond directly to the issue of relevance to economic theory. Tran Huu Dung sees entropy as compatible with mainstream economics, and distinguishes between the entropy implications of consumption, production, and "pure" utility. "Pure" utility refers to satisfaction derived from the natural world without intervention in it, and is neutral in entropy terms. Consumption necessarily increases entropy. Production is more complex: it decreases entropy in some parts of the system while increasing it in the larger environment. This gives a new twist to "technological optimism." The true potential of technology is seen to lie in its ability to achieve utility while minimizing increases in entropy. This has a clear parallel with the standard economic conception of maximizing utility while minimizing costs, but also a crucial difference. The difference is that the entropy implications of a particular production process will probably not be reflected in market prices, nor will consumers be encouraged to favor "pure" utility over consumption through market processes (quite the contrary if advertising is taken into account).

Jeffrey Young, by contrast, defends the mainstream economists' treatment of the entropy law as irrelevant to economic analysis. The essence of his critique is the proposition that technological progress can overcome any growth limitations imposed by entropic degradation. This is linked to an assertion that the entropy concept is meaningless as applied to matter, since improved technology can render previously unusable materials useful. Counter-arguments by Townsend and Daly reemphasize the point that technological progress is always subject to the entropy law, which as a matter of scientific definition applies both to matter and energy. Daly also points out that improved information may constrain rather than expand our choices in use of matter and energy, when we discover unsuspected environmental damage from existing technologies such as CFC's. This is a point of far-reaching importance: the environmentally destructive nature of the "unforeseen consequences" attendant on technological progress often seem to be associated with efforts to "bootleg entropy." For example, the spread of energy-intensive agriculture has brought in its wake a multitude of negative environmental impacts not associated with traditional agriculture. One interpretation of this would be that traditional agriculture, like natural ecosystems, was well-organized for the capture of the solar low-entropy flux; intensive agriculture expands apparent carrying capacity at the expense of polluting the environment with high-entropy waste products. In any event, one inference is that the specific examination of production processes in entropy terms will be intellectually fruitful.

R. Stephen Berry's article moves towards a practical application of entropy analysis with an examination of the thermodynamic efficiency of automobile production. He identifies enormous inefficiency in production techniques viewed not from a least-cost point of view but in terms of energy requirements. Significant energy savings are also possible from recycling or improving product durability, but these are dwarfed by the potential of highly energy-efficient production techniques. Oddly, this thermodynamic inefficiency is probably "efficient" from the point of view of standard economic theory - energy prices are too low relative to capital and labor to justify private investment in energy-efficient plant, or social investment in the appropriate training and infrastructure for a high energy-efficiency economy.

The contrast between economic and thermodynamic efficiency is further developed in the article by Robert Ayres and Indira Nair. They criticize the standard economic concept of a production function with unlimited substitutability between labor/capital and matter/energy. Technology which operates specifically to increase thermodynamic efficiencies can lower matter/energy requirements, subject to entropy law limits, but will not eliminate the problem of economic dependence on high-quality fossil fuel resources. This suggests that analysis of fossil fuel use, reserves, and efficiencies has a specific importance which is not adequately reflected by changes in market price. Such analyses have been attempted by, among others, Robert Costanza, Cutler Cleveland, and Howard and Elizabeth Odum.

What is meant by the "energy cost" of production? The question is trickier than it might appear. One approach is simply to measure the money costs of directly purchased energy (e.g., coal burned in the production of steel). But this leaves out many indirect energy inputs (e.g., energy used to make machinery for the steel mill). It also omits solar energy. We can also consider labor inputs to be indirect energy inputs, at least in part, since the provision of labor requires food energy, energy for housing and transportation, etc. An early review of these issues by P.F. Chapman sets out these problems, and some of the methods appropriate for resolving them, with some specific industrial applications. It is notable, however, than no single entirely consistent technique is identified. Chapman warns that energy studies are subject to misinterpretation if their assumptions and methods are not made clear. These potential ambiguities in energy analysis can become the source of considerable controversy, as the selections in this section demonstrate.

In "Energy and Money" Howard and Elizabeth Odum identify virtually all economic activities as energy flows, balanced by money flows in the economic system. In effect they pose an "energy theory of value" analogous to Marx's labor theory of value. They do not come to grips, however, with the many economic theory difficulties created by such a sweeping simplification. Marx and his followers spent much time grappling with the "conversion problem" of labor value and use value, but the Odums simply overlook any such problems arising from an energy theory of value. They maintain, for example, that inflation arises when money supply growth exceeds available energy supply - an apparently apt description of the energy price-driven inflation of the 1970s, but not very useful analytically in explaining varying rates of inflation during other periods in economic history.

Costanza's 1980 paper, "Embodied Energy and Economic Evaluation," also grapples with the problem of energy valuation. Input-output techniques allow economic inputs to be reduced to primary factors - the question is which primary factors to select. Costanza starts with the conventional categories of capital, labor, natural resources, and government services, then moves by stages to include solar energy, convert labor and government services to their embodied energy equivalents, and then combine these two steps to produce an economic system where energy is in effect the only ultimate input. His main conclusion from a statistical analysis of this model is that embodied energy values are closely related to dollar values of output. Unfortunately this result is vulnerable to the criticism raised by Georgescu-Roegen in "The Entropy Law and the Economic Process in Retrospect" (see previous section). Once all inputs are reduced to energy, the assertion of a constant relationship between energy and output value becomes a tautology. Energy intensity can only vary across sectors if there is some other primary factor contributing to cost of production. By eliminating *all* other primary factors, Costanza may have gone a bridge too far. It might have been better, for example, to base the analysis on the primary factors of solar energy, fossil fuel and nuclear energy, materials, and labor. This would allow investigation of economic shifts over time from dependence on labor and solar energy to fossil fuel/nuclear reliance, and perhaps provide insight into the possibility of an information-intensive future economy based on skilled labor and efficient capture of solar energy. By contrast, what Georgescu-Roegen refers to as the "energetic dogma" is ultimately barren of analytical value.

The article by Cleveland, Costanza, et al., on "Energy and the U.S. Economy" focuses on some more practical conclusions. They demonstrate a strong link between fossil fuel inputs and economic output using a conventional GNP measure. Growth in labor productivity over time is seen not as a disembodied technological advance, but as resulting specifically from increased use of energy in combination with labor. Both of these are important empirical results (though subject to challenge - see for example work by William Moomaw on differing national energy development paths[2]). Their comments on inflation are similar to those of the Odums and subject to the same criticism. Perhaps the most important finding of this article is that the energy costs of obtaining energy itself are steadily rising for all fossil fuel sources. This is a more sensitive gauge of the limits of the fossil fuel age than simple estimates of existing reserves.

Cleveland extends this approach in his 1990 article "Natural Resource Scarcity and Economic Growth Revisited" to examine energy use in all major natural resource sectors of the US economy. Energy costs per unit of physical output are found to be rising in many sectors, giving an important new perspective on the analysis of resource scarcity. Net costs of resource extraction may be falling due to lower labor and capital costs, and still-cheap fossil fuels. But this standard economic measure of costs masks the increasing dependence on energy inputs - and, as noted above, the energy cost of extracting fossil fuels is itself rising. Without significant future increases in energy efficiency or shifts to solar energy, this indicates a predictable future economic crisis, one which is not likely to be reflected in standard economic analyses until it is well under way. The article by John Peet supports this point, using the concept of net energy to measure resource quality, and predicting much higher long-term costs of energy resource development as more easily available, higher-return sources are exhausted.

Bruce Hannon suggests that in this context of energy limits, we face a choice between continuing our energy-intensive economic strategies, or shifting our ethos and incentive systems toward a "conserver society." In such a society, labor and capital would be substituted for energy use. In addition to the environmental advantages, this approach would promote full employment of labor. A tax on energy is the obvious policy tool to promote this economic transition. Such a tax need not be an *additional* burden on taxpayers, but rather should partly replace present taxes on labor and capital. To those who complain that such a tax would distort free market pricing, one might suggest that the present tax system is an equal distortion, but one which is not so benign in terms of its effects on employment and the environment.

A different perspective on the "conserver society" is offered in articles by Robert Ayres and Faye Duchin. Ayres interprets physical flows in the economy in thermodynamic terms: a massive one-way flow of energy and materials being converted to wastes. The emerging concept of industrial ecology suggests a goal of improving process efficiency and reuse of wastes, just as natural ecosystems have evolved for efficient use of low entropy. Ayres points out that the economic incentives of market price often work against this goal, rewarding throwaway products and reliance on virgin materials. He discusses a possible future economy using a solar/hydrogen energy base, and eliminating dissipative uses of heavy metals and other long-lived pollutants. His article is rich in specific examples of the physical and chemical characteristics of industrial processes. It is clear from the discussion that an unguided market economy lacks appropriate incentives to promote the transition to a thermodynamically efficient industrial ecology.

A more specific approach to industrial ecology is presented by T.E. Graedel, et al. Three subsystems of the industrial process are identified: materials production, product manufacture, and consumer product cycle. Each can include both recycling and waste disposal. An overall systems analysis is needed to identify possibilities for more effective materials reuse, reduction, or recycling. The institutional requirements for linking these separate phases of the industrial process may be lacking, with materials producers, manufacturers, and consumers responding to market price incentives only. Modification of these market incentives through, for example, a tax on virgin materials, is one policy tool available for industrial ecology. In other cases more specific regulations aimed at emissions reduction, institutions for collecting and recycling wastes, toxic materials manifest systems, etc., are essential. None of these policy tools are new in themselves, but their comprehensive application to the materials/manufacturing/ consumption cycle is the special domain of industrial ecology.

Faye Duchin offers a specific analytic framework for evaluation of material and energy flows and waste reduction. Her adaptation of dynamic input-output analysis to the industrial ecology perspective crosses the disciplinary boundaries of economics, engineering, and the physical sciences. Its physical focus distinguishes this approach from standard economic optimization techniques based on price signals. Dynamic input-output analysis is particularly appropriate in meeting the challenge posed by Ayres of massive industrial adaptation rather than incremental change. Duchin has also applied this analytical approach to specific areas of industrial ecology, including biomass waste recycling and global strategies for reduction of atmospheric pollutants.[3]

Thus the field of energy and resource flow analysis has developed considerably beyond the broad world-view of economic activity and entropy set forth by Georgescu-Roegen in 1971. Specific techniques and methodologies have emerged, not without controversy, and have been successfully applied to practical problems. Much remains to be done in this area. If the general trends indicated by Cutler Cleveland's work are confirmed by further studies, the importance of this area of investigation will grow. Industrial ecology studies, whether of regional or global scope, will clearly be in increased demand as nations struggle to integrate environment and development issues. The techniques of standard economics are not irrelevant to the investigation of these areas, but a strong case has emerged that they are not sufficient, and may be misleading without a stronger focus on the physical basis of economic systems.

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1. Robert M. Solow, "The Economics of Resources or the Resources of Economics," *American Economic Review* (May 1974).
2. William R. Moomaw and D. Mark Tullis, "Charting Development Paths: A Multicountry Comparison of Carbon Dioxide Emissions," *Industrial Ecology and Global Change*, ed. Robert Socolow (Cambridge, England: Cambridge University Press, 1994).
3. Faye Duchin "The Conversion of Biological Materials and Wastes to Useful Products," *Structural Change and Economic Dynamics*, 1 (December 1990); and Faye Duchin, "Prospects for Environmentally Sound Economic Development in the North, in the South, and in North-South Economic Relations: the Role for Action-Oriented Analysis."