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In the midst of current debates regarding environmental policy, standard economic models have often been criticized for their unsophisticated and unrealistic treatment of the crucial role of natural resources in human economic affairs. Many of these critiques spring from a broad body of research known as biophysical economics. Biophysical economics uses thermodynamic and ecological principles that emphasize the role of natural resources in the economic process. Although the emergence of a palpable environmental and ecological consciousness is a relatively recent phenomenon, the origins of biophysical economics are, in fact, far older. Dating back as far as the Physiocratic economists of the 18th century and the formulation of the laws of thermodynamics in the early 19th century, it is an area of research that has continued to evolve up to the present.

Two themes characteristic of biophysical economics will be used to trace its development. The first theme is the emphasis on the physical laws governing the energy and matter transformations that form the basis of the production process. Ignoring these constraints has resulted in an inadequate accounting of the qualitative changes in natural resource inputs and the vast quantity of wastes that the natural life support system has had to absorb. The second theme is the physical interdependence between the factors of production. The supply of capital and labor depends upon inputs of low-entropy matter and energy, since neither labor nor capital can physically create natural resources. This approach challenges the "omnipotent technology" hypothesis central to neoclassical analysis, which claims that factor substitution will be an adequate response to resource depletion.

Physiocracy, a French school of thought developed in the 1750s, had as its first premise the principle that natural resources, and especially arable land, were the source of material wealth. The Physiocrats maintained that economic processes could be understood by focusing on a single physical factor: the productivity of agriculture. If human society accurately deduced the proper economic behavior implied by "natural law," social welfare would then be maximized. Although few of the Physiocrats' biophysical principles are evident in subsequent theory, their steadfast belief that nature was the ultimate source of wealth has become a recurring theme throughout biophysical economics.

The physical and ecological basis of economic production intuitively grasped by the Physiocrats was formalized by the discovery of the laws of thermodynamics. Thermodynamics and the study of energy flows became a universal index by which many disparate biological and physical processes could be quantified and compared. Carnot showed that thermodynamic laws are essentially economic formulations of physical relations, as they concern the ability of the economy to use energy to upgrade the organizational state of natural resources into useful goods and services. Some 19th century scientists, including the physicist Joseph Henry and the biologist-philosopher Herbert Spencer, emphasized the energy flow basis of social and economic action. The German chemist Ostwald attempted to incorporate thermodynamics into a general theory of economic development, while the Ukrainian socialist Podolinsky tried to reconcile the labor theory of value with a thermodynamic analysis of the economic process. Podolinsky's biophysical analysis led him to conclude that the ultimate limits to growth lay not in the relations of production but in physical and ecological laws.

The early 20th century was characterized by a growing body of literature devoted to the analysis of the role of natural resources in human affairs, particularly in economic production. Among the most notable contributions were those of Frederick Soddy, a Nobel Laureate in chemistry, who applied the laws of thermodynamics to economic systems and devoted a significant part of his life to a critique of standard economic theory. Like the Physiocrats, Soddy maintained that a comprehensive theory of wealth must have biophysical laws as its first principles since "life derives the whole of its physical energy or power . . . solely from the inanimate world."[1] He particularly emphasized the centrality of solar energy in empowering the life process.

The use of energy as a unifying concept for social, political and economic analysis reached a zenith with the technocratic movement in the US and Canada during the 1930s. Members of this movement believed that energy was the critical factor determining economic and social development, and they advocated the idea of measuring vital economic parameters in energy units instead of dollars. They believed that politicians and businessmen could not manage a rapidly advancing industrial society and should therefore be replaced by scientists and engineers, who possessed the requisite expertise to manage the economy towards a highly idealized future.

The 1950s was an exceptional period for research on the role of energy and natural resources in social and economic development. The most comprehensive study was made by a sociologist, W. F. Cottrell, whose work focused on what he termed "surplus energy," i.e., the difference between the energy utilized in energy delivery and the amount of energy recovered. He also stressed the role of energy in enhancing labor productivity. Cottrell examined the differences between biophysical and humanist approaches to biological and cultural evolution, and argued that resource availability and energy use set the general direction for social change.

Like Cottrell and others, M. K. Hubbert, a geophysicist writing at about the same time, was impressed by the correlation between the burst of human civilization and the transition to a fossil fuel economy. He used his vast knowledge of physics, mathematics and geology to revolutionize the way in which the supply of nonrenewable resources was analyzed, and was the first to predict that the fossil fuel era would be relatively short lived. Hubbert's petroleum supply models have proven to be remarkably accurate; it is ironic that the only model correctly predicting the peaking of domestic oil production in the US was from a physicist.

The amount of research devoted to energy-environment-economic interactions increased substantially in the wake of the environmental movement and the petroleum crisis of the 1970s.

H. T. Odum developed a systematic methodology using energy flows to analyze the combined system of humans and nature. One of Odum's most important contributions was an analysis of the countercurrent flows of energy and money in the economy. He pointed out that whenever a dollar flow exists, there must be an energy flow in the opposite direction. Moreover, while money circulates in a closed loop, low-entropy energy enters the system and is consumed in economic tasks. Other essential energy flows (e.g., solar, water, wind, etc.), have no associated dollar flow, leading to their misuse. Empirical support for some of Odum's ideas was provided by Costanza, who analyzed the relationship between the "embodied energy" (direct and indirect energy) used to produce a good or service in the US economy and the dollar value attached to that good or service in market transactions. Geologist Earl Cooke provided a comprehensive overview of energy systems and industrial society in his 1976 book, Man, Energy, Society.

The Energy Research Group (Hannon, Herendeen, Bullard, et al.) at the University of Illinois greatly enhanced the empirical methodology of biophysical economics with an input-output model of the US economy based on energy flows, from which the direct and indirect energy cost of any good or service could be calculated. Hannon used this information to argue for a strong energy conservation ethic. Like Soddy and the technocrats, he believed that the existing economic system was an inadequate allocator of energy and other natural resources. Robert Ayres developed a materials-energy balance model to describe the inconsistency of the closed, cyclic model of standard economics. He showed that economic production necessarily generates high-entropy wastes - i.e., negative externalities - which are treated in standard economic theory as isolated market failures, but which are in fact an inevitable and pervasive outcome of economic production.

Some of the most insightful developments in biophysical economics during the 1970s are from Nicholas Georgescu-Roegen and Herman Daly. Georgescu-Roegen depicted a unidirectional flow in the economy, from inputs of low-entropy energy and matter, to outputs that included both useful goods and services and valueless high-entropy waste heat and degraded matter. By focusing on the circular flow, standard economic theory loses sight of the sensitivity of economies to changes in the quality of nature's low-entropy stocks of resources and the degrading of basic natural life support processes.

In his 1977 book, Steady State Economics, Daly points out the logical inconsistency of the emphasis placed upon growth in the context of the energy and environmental realities that we confront. Like Ayres, Daly criticizes the failure of standard economics to take account of the throughput of low-entropy natural resources, from which all goods and services are ultimately derived. Our preoccupation with monetary flows at the expense of thermodynamic principles misleads us into believing that perpetual economic growth is not only possible but morally desirable as well.

The majority of economists reject biophysical economic models, arguing that they underestimate the ability of technological innovation to offset changes in resource quality (e.g., Barnett and Morse[2] (1963), and Solow[3] (1974)). However, the biophysical perspective does acknowledge the importance of human ideas, but it also stresses that they must be firmly rooted in the biophysical world; to date, most of our technological innovations have relied upon increased fossil fuel use per worker. Economics can no longer afford to ignore, downplay, or misrepresent the role of natural resources in the economic process.

Notes

1. Frederick Soddy, *Cartesian Economics* (London: Hendersons, 1922), 9; cited by Cleveland, 52.
2. H.J. Barnett and C. Morse, *Scarcity and Growth* (Johns Hopkins University Press, 1963)
3. R.M. Solow, "Intergenerational Equity and Exhaustible Resources," *Review of Economic Studies*, 1974, 29-45.