Environment, Power, and Society for the Twenty-First Century: The Hierarchy of Energy

Howard T. Odum

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ENVIRONMENT, POWER, AND SOCIETY

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To Howard Washington Odum

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FOREWORD

With the publication of *Environment, Power, and Society* in 1971, H. T. Odum changed the lives of countless individuals; altering their worldview by starting them along a quantitative, systems-oriented path toward holistic thinking. He introduced them to the Energy Systems Language, a visual mathematics capable of representing the details and bringing into focus the complexities of any system, and to the "macroscope," his tool for eliminating details and gaining an overview of the entire system. For many of us *Environment, Power, and Society* was profound, a book that cleared away much of the mystery about how the world works and that provided extraordinary insights into why things are the way they are. It was in *Environment, Power, and Society* that we learned "industrial man . . . eats potatoes partly made of oil," and "money . . . is fed back in reward for work done" and therefore acts as a pathway selection mechanism for society. In this book, we first read the "ten commandments of the energy ethic for survival of man and nature" and took to heart "thou shall not waste potential energy." It was in *Environment, Power, and Society* that H. T. Odum developed his concept of "ecological engineering," which later became the basis for academic programs at several major universities; a journal by that name; and an international society. His statement in 1971 that, "The science of economics may profit by restating more of its theorems to include power principles," and subsequent years of doing just that, eventually led to the new field of ecological economics, which now has its own international society and journal.

Most important, however, *Environment, Power, and Society* helped many of us to understand the interrelationships of energy and environment and their importance to the well-being of humanity and the planet. His goal was always to gain understanding through unifying rather than dissecting, through aggregating rather than disaggregating. In his life he was constantly engaged in a zealous search for truth and understanding regardless of where that search carried him. H. T. often wrote of his desire to simplify to increase understanding . . .

"If the bewildering complexity of human knowledge developed in the twentieth century is to be retained and well used, unifying concepts are needed to consolidate the understanding of systems of many kinds and to simplify the teaching of general principles" (Odum 1994).

H. T. Odum was a scientist and teacher who left an incredible legacy of books, ideas, and teachings. His love of teaching, his creative and imaginative way of viewing the biosphere, his grasp of many different fields of science, and his drive and unbounded energy have left many students, colleagues, and associates awestruck. His unique way of understanding the biosphere and humanity's place within it was his gift to us all. This gift will, without question, endure and expand as it is more fully understood by this and succeeding generations. Although he left us a legacy of books, research publications, and scientific papers (see Brown and Hall 2004), his devotion to the welfare of his students, close associates, family, and humankind stands far beyond these tangible products of his scientific inquiry. In his own words in *A Prosperous Way Down* (Odum and Odum 2001), his most recent book with his wife Betty, he said, "As sometimes attributed to past cultures, people may again find glory in being an agent of the earth." H. T. Odum was an agent of the earth, striving always to teach partnership with nature that encompasses and transcends good stewardship and a profound respect for the cycles and hierarchies of the biosphere.

In the summer of 2002, H. T. Odum was diagnosed with brain cancer. Much earlier, he had arranged with Columbia University Press for the publication of this second edition and was in the process of revising the manuscript when this devastating news was revealed. He worked diligently on the final revision until his death in the fall of that year. Mark Brown; Elisabeth Odum, his wife; and Dan Campbell made a promise to finalize the manuscript and see it published. Our deep gratitude is due to Dr. Robin Smith, former Senior Executive Editor for the Sciences, at Columbia University Press, for his patience and continued encouragement toward finalizing the manuscript, and to Patrick Fitzgerald, science publisher, who worked tirelessly with us to make this book a reality.

More than thirty years have passed since publication of *Environment, Power, and Society*. With the publication of *Environment, Power, and Society for the Twenty-first Century*, we see how the ideas and themes introduced thirty-five years ago have played out and been advanced by H. T. Odum, his colleagues, and his students. In our estimation, this book is even more profound than his first book, as it contains the fruits of thirty more years of systems thinking by one of the world's most revolutionary systems scientists and ecologists. We hope that *Environment, Power, and Society for the Twenty-first Century* will have an even greater impact throughout the world and that once again there will be students who find their lives changed after reading this book, as happened to so many of us lucky enough to find Odum's first book in the early 1970s.

Mark T. Brown
Gainesville, FL

Elisabeth C. Odum
Gainesville, FL

Daniel E. Campbell
Narragansett, RI

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PREFACE

THIRTY YEARS have passed since the original edition of *Environment, Power, and Society* was published. Since that time the world has had a taste of living with global fuel shortage, high prices, and the ensuing inflation of 1973–1983. Accelerated economic growth resumed aided by new discoveries of natural gas. The Persian Gulf wars have been fought, in part, to keep global fuel reserves on the free market. With the spread of computers and the internet, many authors wrote of the "unlimited potentials of information," just as they wrote of the potentials of nuclear energy four decades ago. But a look at nature shows limits to information. Belief spread in the paradigm that all systems pulse, and many writers warned of the downturns ahead in the global pulse of affluence in developed countries, based on converging resources from the rest of the world.

People with knowledge of the details of our planet have mixed feelings when much of the detail is aggregated in order to develop simple views from a larger scale. In the quest for knowledge and in the practicality of earth management, all scales are of importance, each in its place. What has been missing in much of the past century in science and public education is teaching an imperative to view each scale in aggregated simplicity from the next one larger. Science has become conservatively rigid by overemphasizing the half right cliché that to be basic is to look smaller to the fundamental parts.

The new title, like the original book of some thirty years ago, is based on energy systems synthesis of the parts and processes of systems, a diagrammatic way of showing important relationships constrained by the limitations of materials, energy, money, and information. Whereas many inferences in 1970 were made by qualitative study of systems diagrams, simulation of models has since become a general practice. Models like those previously diagrammed, and thousands of others like it, have been published widely by a generation of systems thinkers. The energy systems language has been widely used to show main parts, pathways, and relationships of systems.

In the original volume, published when simulation was new, there was a chapter on concepts for analog and digital simulation of energy models over time. In the intervening years we have simulated most of our overview minimodels, and these are included where relevant in this book rather than in a separate chapter. Details on simulation methods are given in our recent book: *Modeling for All Scales* (Academic Press, 2000).

For the progress in developing and applying concepts over these intervening years since the publication of the first volume, I gratefully acknowledge the shared mission with students and faculty associates at the University of Florida. Elisabeth Chase Odum was a partner in our efforts to develop energy systems concepts for global education. Joan Breeze was editorial assistant.

Howard T. Odum,
Gainesville, Florida
November 2000

CHAPTER 1

THIS WORLD SYSTEM

THIS BOOK is about nature and humanity. Nature consists of animals, plants, microorganisms, earth processes, and human societies working together. These parts are joined by invisible pathways over which pass chemical materials that cycle around and around, being used and reused, and through which flow potential energies that cannot be reused. The network of these pathways forms an operating system from the parts. Behavioral cues pass between animals; human discourse and money organize society. A study of humanity and nature is thus a study of systems of energy, materials, money, and information. Therefore, we approach nature and people by studying energy systems networks. The idea is to use general systems principles to understand and predict what is possible for society and environment.

Figure 1.1 shows the essence of our system of environment, power, and society. Energy from the sun and from the earth is running the landscape and its links to humanity. The quantity of useful energy determines the amount of structure that can exist and the speed at which processes can function. The small areas of nature, the large panoramas that include civilization, and the whole biosphere of Earth and the miniature worlds of ecological microcosms are similar.[1] All use energy resources to produce, consume, recycle, and sustain.

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FIGURE 1.1 System of environment, power, and society in the geobiosphere, which has inflowing solar energy, earth energy from below, cycling of materials, circulation of money, and feedback of human services to nature. This diagram, drawn by the author on a computer, is the logo for the Center for Environmental Policy at the University of Florida.

The Macroscope

In the 1600s, when Leeuwenhoek ushered in the Enlightenment through the study of the invisible world with the microscope, and when some of the atomistic theories of the Greeks received step-by-step observable verification in chemical studies, concepts of the structure and function of the natural world emerged as parts within parts within parts. Many of the advances of human civilization have come from these microscopic dissections. Yet in the 21st century the ever-accelerating knowledge of the microscopic view has not provided us with the solutions to problems with the human environment, social systems, economics, and survival, for the missing information is not wholly in the microscopic components or in identification of the parts. On the familiar scale of human life, we see the parts very well (people, economic assets, environmental components), but rarely do we think of it as a single-system operation. Pioneering thinkers such as V. I. Vernadsky (1926) recognized the intricate interdependence of humans in the processes of the earth, but many regard the scale of human life as free of controlling principles.

Astronomical systems, although infinitely larger, are seen through such distances that only the main features show (chapter 4). But on Earth, progress in understanding is slow because we are too close to see. As in the old adage about the forest and the trees, we cannot see the pattern for the parts. Figure 1.2 is a cartoon view of the steps we must take in going from detailed data to system viewing and prediction, a process we call using the macroscope. Whereas people often search

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FIGURE 1.2 Cartoon of the macroscope and the steps in its use. The detail eliminator simplifies by grouping parts into compartments of similar function.

among the parts to find mechanistic explanations, the macroscopic view is the reverse. Humans, already having a clear view of the parts in their fantastically complex detail, must somehow get away, rise above, step back, group parts, simplify concepts, and interpose frosted glass to somehow see the big picture.

Since *Environment, Power, and Society* was published, many sciences have found better lenses for the macroscope, better ways to see how the parts form larger wholes and patterns. Networks are better understood with new mathematics, models, and computer simulations that join the parts to show how the larger systems perform. The world is finally using the macroscope by viewing global problems on television, traveling worldwide, exchanging information on the Internet, and discussing global policies, politics, and international trade. The daily maps of worldwide weather, the information received from the high-flying satellites, macroeconomic statistical summaries, the combined efforts of international geophysical collaborations, and the studies of cycling chemicals in the great oceans all stimulate the new view.

In this book, therefore, the reader is invited to view the world and society through the macroscope. Many explanations use the principles of energy hierarchy (chapter 4). We hope to show the great wheels of the machinery in which we are small but important cogs and perhaps in the end predict how the earth will program human services in the drama of the earth.

The Biosphere

We can begin to gain a systems view of the earth by looking through the macroscope of the astronaut high above the earth. From an orbiting satellite, the earth's living zone appears to be very simple (fig. 1.3c). The thin water- and air-bathed shell covering the earth—the biosphere—is bounded on the inside by dense solids and on the outside by the near vacuum of outer space. Past the orbiting capsule radiant energy from the sun enters the biosphere, and soon equal amounts pass outward as flows of heat radiation. Through the haze of height only a few features of energy flows can be observed. There is a great sheet of green chlorophyll and cyclones of spiraling clouds in weather belts, but the miraculously cascading machinery of parts within parts within parts is not even visible. From the heavens it is easy to talk of gaseous balances, energy budgets per million years, and the magnificent simplicity of the overall metabolism of the earth's thin outer shell. With the exception of energy flow, the geobiosphere for the most part is a closed system of the type whose materials are cycled and reused.

The biosphere is the largest ecosystem, but the forests, the seas, and the great cities are systems also. Large and small parts operate on their budgets of energy, and what can and cannot be done is determined by energy laws (chapter 3). Any phenomenon is controlled both by the working of its smaller parts and by its role in the larger system of which it is a part.

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FIGURE 1.3 Closed-to-matter systems supported entirely by sunlight and their metabolic reactions. **(a)** Aquatic closed system; **(b)** terrestrial microcosm; **(c)** biosphere of Earth; **(d)** Biosphere 2 in Arizona; **(e)** diagram showing energy flows for the systems **(a–d)**; **(f)** cycle of materials between photosynthetic production (P) and respiratory consumption (R); **(g)** summary equations for photosynthetic production and the reverse process of respiratory consumption.

The work that results from energy flow is inherently hierarchical, with many calories of one kind required to produce a few calories of another. Much of the organization of the geobiosphere and the human economy is understandable from the energy hierarchy concepts (chapter 4).

In earlier times, energy available to human management was insufficient to control the biosphere, and people were protected in their ignorance by the great stabilizing storages of the oceans and atmosphere. In recent years, however, the accelerating growth of fossil fuel use has allowed civilization to interfere with life support, outdistancing our knowledge of the consequences. The gaseous emissions of civilization are changing the climate (chapter 5).

The Living Metabolism of the Earth

With the turning of the earth, the sun comes up on fields, forests, and fjords of the biosphere, and everywhere within the light there is a great breath as tons upon tons of oxygen are released from the living photochemical surfaces of green plants, which are becoming charged with food storages by the onrush of solar photons. Then, when the sun passes in shadows before the night, there is a great exhalation of carbon dioxide (CO_2) that pours out as the oxygen (O_2) is burned, the net result of the maintenance activity of the living machinery. During the day, while oxygen is generated, a great sheet of new chemical potential energy in the form of organic matter lies newborn about the earth, but in the darkness, the new organic matter and oxygen disappear in hot and cold consumption processes that release heat through the night. Figure 1.3e and 1.3g summarizes earth metabolism.

The living process in green chlorophyll of forests, lakes, oceans, and deserts during the day is called photosynthesis by those who study a small segment of it and primary production by those who consider great masses of it. In photosynthetic production (abbreviated *P* in fig. 1.3), carbon dioxide, water, and nutrients are combined to make organic matter and oxygen.

Consumption of organic matter and oxygen by living organisms and by cities goes on day and night but is masked by primary production of these substances during the day. It can be measured at night. Although *respiration* usually is used for the cool fires of biological consumption, let us also allow the word to include consumption by the hot fires of autos and industry. The letter *R* is the abbreviation used here for all such consumption. Respiration transforms the energy of food and fuel consumption into useful work when the organic molecules are combined with oxygen to make carbon dioxide and water (fig. 1.3g). In the overall equation for consumption, materials are returned to the inorganic state, ready for primary production again (fig. 1.3f). The materials generated by consumption are the ones used by production and vice versa.[2]

The average *P* and *R* of the biosphere has been about 1 g of organic matter per square meter per day. This is about 4 kcal of organic potential energy stored daily as organic matter and burned again later (Behrenfeld et al. 2001). Together the *P* and *R* processes generate a cycle of materials. Systems running on sunlight that are closed to matter tend to develop a balance between production and consumption. Like the biosphere, three other solar-based systems that are mostly closed to matter are shown in fig. 1.3: an aquatic microcosm, a terrestrial microcosm, and the 3-acre Biosphere 2 in Arizona (Marino et al. 1999).

Resources from Above and Below

About half of the energy that comes to the earth from the sun is in the visible wavelengths, which are used in photosynthesis. The other part of solar energy is in infrared and ultraviolet light wavelengths that are absorbed as heat in the ocean, soils, and vegetation. This directly absorbed heat, plus the heat released from photosynthetic machinery using the visible wavelengths, plus heat released when organic matter is consumed, all add together to cause higher temperatures near the equator and lower temperatures in shaded regions. Between high- and low-temperature areas a giant heat engine operates, creating the great wind and water current systems of the earth. The energies processed by the earth's heat engines contribute to photosynthetic and respiratory processes by causing winds and water currents to bring raw materials such as rain and fertilizer minerals more rapidly to the plants for production.

Some of the sun's heat drives the plant's uptake of water from the soil and the transpiration of water from its leaves. Other winds and currents aid food chains by moving organic matter to the sites of consumption. Hence, the *P* and *R* processes of the biosphere are closely linked energetically with the earth's physical processes, its heat, winds, and water currents (see chapter 5).

The biosphere also receives potential energy from the pull of the sun and moon that drives the tidal currents. Available energy with the potential to do work also enters the biosphere from the earth below. The land is renewed by geologic cycles that push land to the surface to keep up with the land that is eroded away. Some of this work is driven by the circulation of hot, fluid rock deep in the earth. The geobiosphere depends on the support of the earth bringing resources up from the earth below and the tide and solar inputs from above (figs. 1.1 and 1.3e).

Solar Society

During agrarian regimes, with people and domestic animals living off the land, there was often a balance of primary production and total respiration (consumption) in the course of the year. The net annual effect on the gases of the atmosphere, on the concentration of minerals, or on the future was small, for the system was balanced as an aquarium is balanced. Some organic matter was stored as fuel and oil, but the amount per year was tiny. As agrarian systems multiplied the world over, the biosphere was little disturbed; production and consumption were similar on average.

When human societies first evolved as a significant part of the systems of nature, people had to adapt to the food and fuel energy flows available to them, developing the familiar agrarian patterns of human culture. Ethics, folkways, mores, religious teachings, and social psychology guided the individual's participation in the group and provided means for using energy sources effectively. Sunlight is spread out over the earth's surface so evenly that it is not directly available to people until after some of it has been concentrated. Much of the sun's potential is necessarily used up by the concentrating processes through plants and animals. Societies that were able to survive had to gather food and distribute energies within the social system for their successful continuance, and they developed the group organization necessary for these purposes. The social systems adapted to meet changing conditions such as overcrowding, fluctuations of yield, crises from competitors, and threats from internal disorder. The pattern of solar society is shown in fig. 1.4a. Its main parts and processes run on outside resources, the sunlight from above, the tides driving the ocean, and the geologic processes bringing energy and materials up from the earth below. The economic system was simple, and economic reward often reflected the energy control gained.

Humanity Takes Over Nature with Fossil Fuels

Over the last two centuries, society's basis has changed, for now much more fuel energy is coming from concentrated sources within the earth. The economy's industrialized system now gets its energies from fossil fuels (coal, natural gas, oil) and nuclear fuels. Much of this energy flow goes back into our environmental system to increase the yield of food and critical materials. Figure 1.4 contrasts the new industrial system and the old agrarian society. The earlier society was dispersed over the landscape because the energy sources were spread over the earth's surface.

Few understand that cheap food, clothing, and housing depend on cheap energy and that potatoes are really made from fossil fuel. High agricultural yields are feasible only because fossil fuels are put back into the farms through the use of farm equipment, manufactured chemicals, and plant varieties kept adapted by armies of agricultural specialists supported by the fossil fuel–based economy.

Adding industrial society to the biosphere suddenly is like adding large animals to a balanced aquarium (Beyers 1963b). Consumption temporarily exceeds production, the balance is upset, food and fuels for consumption become scarce as the products of respiration accumulate. These stimulate production, and the balance of respiration is restored. In some experimental systems, balance is achieved only

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FIGURE 1.4 Comparison of **(a)** an agrarian system with **(b)** an industrialized system. (See chapter 8.)

after the large consumers that originally started the imbalance are dead. Will this happen to the present human culture?

Urban Development and Animal Cities

Now, the highly concentrated fossil fuels cause developments to be concentrated in urban centers. Sometimes we can comprehend the essence of complex human phenomena by looking at the similar but simpler systems of nature (fig. 1.5). The energetic processes of an industrial city are like those in a dense reef of oysters, an animal city (fig. 1.5). Both are operating at high intensity based on an inflow of resources. Both are centers of energy hierarchy. The fossil record of animal cities is beautiful, with the remnant structures of ancient reef ecosystems. But many of the species of these animal cities are extinct. What does the future hold for the industrial economic reefs, our present cities?

During industrial regimes with the system running mostly on fuels, people manage affairs with technology. Even agriculture is dominated by machinery and industries supplying equipment, poisons, genetic varieties, and high-tech services. The industrial society has respiratory consumption greater than photosynthetic production. The products of respiration—carbon dioxide, metabolic water, and mineralized inorganic wastes—are discharged at rates greater than their incorporation into organic matter by photosynthesis. If the industrialized urban system were enclosed in a chamber with only the air above it at the time, it would quickly exhaust its oxygen, be stifled with waste, and destroy itself because it does not have the balanced recycling pattern of the agrarian system.

The problems with life support in the 1970s on *Apollo* space flights and the later experiments with Biosphere 2 in Arizona dramatized this principle to the world (chapter 12). At present, the biological cycles of the environment are barely able to absorb and regenerate agricultural and urban wastes. New kinds of landscapes and interface ecosystems need to evolve with the help of ecological engineering (chapter 13).

Information Society and the Changed Role for Humanity

Late in the last millennium the pattern of society was concentrated into an information society sharing global television, individual computers, and the Internet. More and more electrical power was required. Global information sharing and foreign trade increased. The changes have come so fast that many customs, mores, ethics, and religious patterns have not adapted. The economic system is large, complex, and changing so rapidly that it is more and more difficult for people to see its energy basis (chapter 9). Few people realize that their prosperity comes from sample content of Environment, Power, and Society for the Twenty-First Century: The Hierarchy of Energy