



A picture is worth a thousand words: energy systems language and simulation

Mark T. Brown

Department of Environmental Engineering Sciences, University of Florida, Gainesville, FL, USA

Abstract

A historical perspective of the energy circuit language is given (sometimes called energy circuit language). Beginning with HT Odum's first energy flow diagrams used explain the general organization of ecosystems and the flows of energy supporting production and ending with diagrams of the universe, the 50 year evolution of the energy systems language are explored. Changes in the language often resulted from technological changes in the "tools" of Odum's trade (i.e., the use of drawing software on computers) as well as refinements of his theories related to ecological and general systems theory, hierarchical organization, and energy quality. In all the language represents a concise way of visualizing systems, describing them mathematically, and developing programs for simulating their dynamic behavior.

© 2003 Elsevier B.V. All rights reserved.

Keywords: Energy systems language; Systems simulation; Systems

1. Introduction

The first time I experienced the power of H.T. Odum's symbol language, sometimes called Energy Circuit Language, "Energese" or Energy Systems Language, was at a public lecture held on the University of Florida campus soon after his arrival as Graduate Research Professor in Environmental Engineering Sciences. The year was probably 1971. As I learned later, H.T. purposefully sought out venues across campus in which to lecture during his first months to arouse interest in his systems course. A friend had suggested that I attend.

As only Odum could do, he had something in his lecture for everyone. A little chemistry, ecology, philosophy, meteorology, classical energetics, biology, even religion... punctuated by "overheads" of

diagrams illustrating the concepts. I listened as he described systems of varying scales and complexity and watched as he illustrated his verbal descriptions with his "picture mathematics." Soon there was much interest among the crowd of students in attendance in the systems language itself. So toward the end of his lecture he said, let's draw a diagram of some system, what shall it be? I stated immediately... "A city"... for I had been reading and studying everything I could find on cities and felt I could provide a fair amount of information regarding the parts.

After about 20 min a picture of a city began to emerge that had all my pieces, but they were now logically interconnected through lines representing the flows of materials, energy, and information. I began to see the structure of the city system rather than the jumble of pieces that had made up the mental composition I called city. There on the classroom black board a picture of an urban system emerged with its causality, processes, and parts revealed. Economics, energy

E-mail address: mtb@ufl.edu (M.T. Brown).

and ecology were integrated into a single whole. For the first time after years of study, I began to see the whole . . . as a whole.

That lecture was a transformation. Through the emergence of that city diagram, I began to question whether one could grasp the complexities of “how things worked” by studying pieces . . . whether one could build understanding of complex systems by putting pieces together in the hopes of constructing wholes. As Odum said many times . . . “one needs a microscope to see the whole.”

In many respects Odum’s systems language is a microscope for it forces one to “overview” and diagram the system, the relationships between components, and to think process. It is top down in its approach, for the first thing that one must do when diagramming a system is list its energy, material and information sources . . . the “driving energies” as Odum labeled them. Next the components are listed and then the state variables, and finally the outputs. In those early days when we were still learning the language, after completing the lists of sources and components, a large sheet of paper or a blackboard would be employed and everyone would gather around to suggest how to organize the driving energies and components into a whole, linked by the flows of material, energy, and information.

The language is “picture mathematics.” Each symbol is rigorously and mathematically defined. By drawing a diagram one, in essence, is writing equations that describe the system under study. In fact, Odum suggested that the first step in simulation modeling should be to draw a diagram of the system. The equations describing relationships and processes of the system then emerge, simply, from the diagram. Thinking on the behavior and structure of a system is done in the diagramming. Most importantly, Odum strongly believed that purely mathematical modeling, often had no basis in reality as modelers derived equations for observed system behavior instead of understanding the energetic, chemical, or physical basis for the behavior. As an interesting exercise during seminars, Odum often asked his students to translate mathematical models into energy systems diagrams. The results were sometimes comical as the diagramming exercise revealed the lack of energy sources to sustain production, or the lack of a food source to sustain a population of organisms. In such systems it

was not uncommon for materials, such as nutrients or organic matter, to spontaneously appear at the site of their use in a production equation only to disappear again when that which was produced was consumed.

A theme that Odum returned to again and again was the need to educate the general population in science, so as to produce a “new breed of educated laymen and general scientists . . . to provide leadership in a world where at every turn the factual aspects of science are affecting the decisions of society” (Odum, 1958). He also was convinced that the rate of production of new knowledge and the complexity of that knowledge required tools to simplify, unify, and consolidate understanding. Another theme that Odum stressed again and again was that “The language has the interesting property of showing many entirely different kinds of systems as similar in type” (Odum, 1972a). Thus, its possible to view the complexity of the modern world through a systems microscope and interpret it with systems diagrams to synthesize pattern and process into knowable and predictable behavior.

2. Energy systems diagrams and simulation

One cannot separate the development of the diagramming language from the development of the theoretical underpinnings of Odum’s Systems Ecology nor from the intellectual testing and verification that resulted from simulation. It was through constant feedback between theory, observation, simulation and diagram that the language and its syntax evolved. In yet another co-evolutionary trend, it is impossible to separate the language’s development from the developing computer technologies. Odum, and as a consequence, the language, went through definite “technology stages.” First, he illustrated how the language was easily translated into analog circuit diagrams for programming passive analogs, then later operational analogs and eventually digital computers. A chapter was devoted to simulation in *Environment Power and Society* (Odum, 1971). The majority of the chapter was related to electrical circuits and analog simulation, although Odum, hinting at what was to come, mentioned digital computers and provided a flow chart for programming a simple model.

In the late 1970s and early 1980s as simulation switched from analog to digital the ease with which

one could construct and simulate a model made simulation a dominant aspect of the development of the language.

When digital computers were miniaturized to desktop size from the early computers that were housed in whole buildings, Odum was the first to have one and quickly demonstrated how the language could be translated into sets of differential equations and then to difference equations easily programmed in BASIC. Soon to follow was program after program of the relatively simple “macroscopic minimodels” for teaching purposes. For example, during one summer, Odum developed a booklet of over 30 simulation models complete with systems diagram and BASIC program for systems of many scales... everything from a simple model producing logistic growth to a model of global CO₂ balance. This exercise would culminate years later in the publication of the book *Modeling for All Scales*, written with his wife, Elisabeth (Odum and Odum, 2000). Containing 60 macroscopic minimodels as an introduction to simulation modeling, the book comes with a CD containing programs for all the models in BASIC. The text was intended to introduce modeling and simulation without requiring a mathematical background. It was Odum’s belief that modeling and simulation were intellectually creative ways to connect ideas with reality and that it is high time that everyone engaged in intellectual inquiry, model and simulate the phenomena of his or her interest.

As a side note, it was always most interesting to sit in on Odum’s systems ecology course, where the backgrounds of students varied from liberal arts to the “hard sciences”. As a teacher, he was always able to orchestrate these assemblages into a finely tuned blending of philosophy, science and art keeping each student engaged, confident and intellectually stimulated. One-third of the class grade was a required simulation model relating to the student’s interest. These were some of the most inspiring and interesting simulation models I have ever encountered.

3. A power basis for the energy circuit language

The energy circuit language grew out of a recognition and appreciation for open system thermodynamics of ecosystems, general systems theory, and

simulation. As Odum stated on more than one occasion... “Because the existing symbolic and mathematical languages were inadequate to represent the thermodynamics of real ecosystems, we invented the energy systems language as a generalization of electronic circuits.” (Odum, 1995, Chapter 37, Maximum Power). With the language came the ability to express the 1st and 2nd laws of thermodynamics as well as feedback and eventually maximum power reinforcement. In his early discussions of the language it was used to describe power (energy per time) as a common dominator of all systems. It was a way of describing casual action by showing the flows of casual forces generated by energetic storages. As Odum said in describing the language...

“To understand a whole system and the full interaction of the parts, we must use a common denominator that expresses all the flows and processes together. Power is a common denominator to all processes and materials. If some portrayal of causal action is needed, the network diagrams must show the flows of causal forces. Since forces are generated from energetic storages, their lines of action may also be represented by the same lines that indicate energy delivery. If potential sources of power deliveries are to be shown, the energy storages must also be given.” (Odum, 1971)

The “power” basis for the language gave way to the “empower” basis as Odum recognized the hierarchy of energy transformation networks to be general to all systems. Traditional definitions that equated work and energy were revised because he recognized that available energy of different forms of energy were not equivalent. Odum redefined work as an energy transformation where an input energy is transformed to a new form (or concentration) of “higher quality”. Quoting Odum... “We defined this process as a network concept where work increases the utility of energy while degrading and dispersing part of that energy.” (Odum, 1995) The new concept was first called embodied energy but soon changed to emergy, which lead to defining the flow of emergy and empower (emergy per time). In the late 1990s simulation models included the tracking of emergy and “transformity” (the energy of one type required to generate a joule of another type). Undoubtedly, the language was under transition in the early part of the twenty-first century as Odum

turned his focus to modeling the hierarchy of material cycles, energy, and transformity.

4. Historical development of the language

The energy systems diagramming language evolved with time. The earliest energy diagrams by Odum were flow diagrams like the diagram of a ecosystem having five compartments in Fig. 1 (Odum, 1956). The quantity of energy flowing was illustrated by the width of the line. Necessary losses, as degraded energy, were shown exiting downward. This characteristic, as well as the flow of available energy from left to right, would remain an integral part of Odum's systems diagrams always. Fig. 2 is an analog diagram that is a translation

of the energy flow diagram in Fig. 1, that was used several years later to illustrate the potential for analog simulation of energy flows in ecological systems (Odum, 1960a). In Fig. 3 the varying lines widths are replaced with a single line width with arrow heads indicating direction of energy flow (Odum, 1962). Note that the plants have two components a "solar receptor" and a respiratory function (square box) both of which are enclosed by a dashed line. This is the earliest suggestion of what later would become the combination of the "cycling receptor" and self-maintenance unit into the group symbol for green plant.

In 1963 Odum wrote two papers that contained the first inkling of the energy circuit diagramming symbols (Odum, 1963a,b). Shown in Fig. 4a is a diagram of an ecosystem showing the boundary fluxes

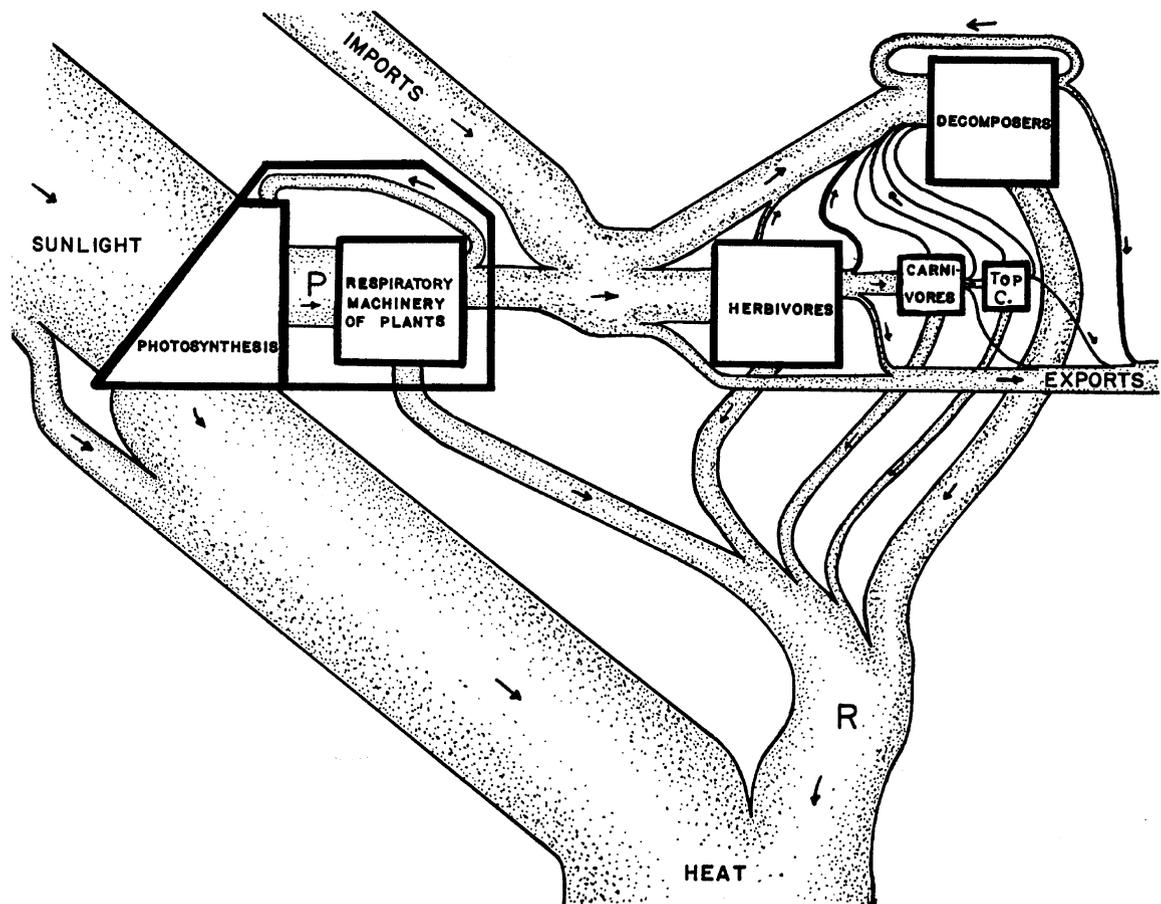


Fig. 1. Energy flow in a "generic ecosystem." The width of line is proportional to the quantity of energy. Arrows indicate direction of flow. P, gross primary production; R, respiration.

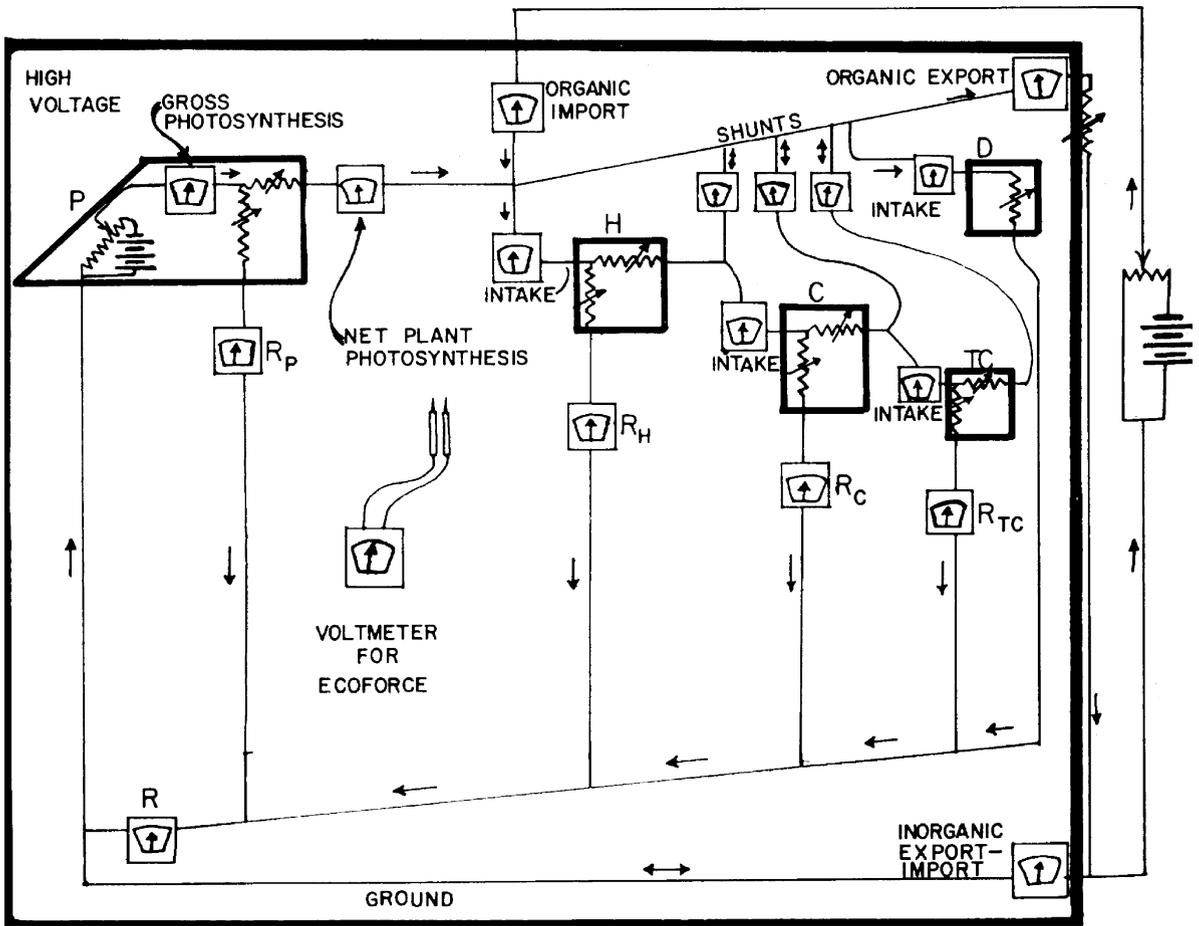


Fig. 2. Analog circuit diagram of the ecosystem energy flow diagram in Fig. 1.

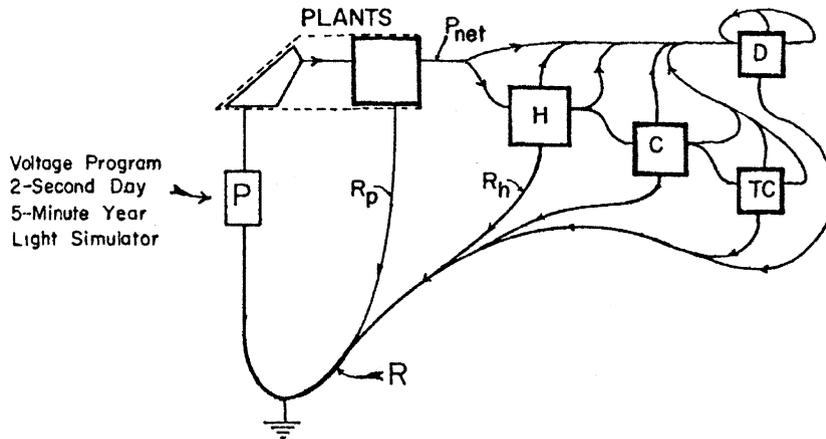


Fig. 3. Main circuits of the ecosystem (c.1962). Thickness of pathways is absent. Direction of flow indicated by arrowheads. Flows and storages are for carbon. P, production; H, herbivore; C, carnivore; TC, top carnivore; D, decomposer; R, respiration.

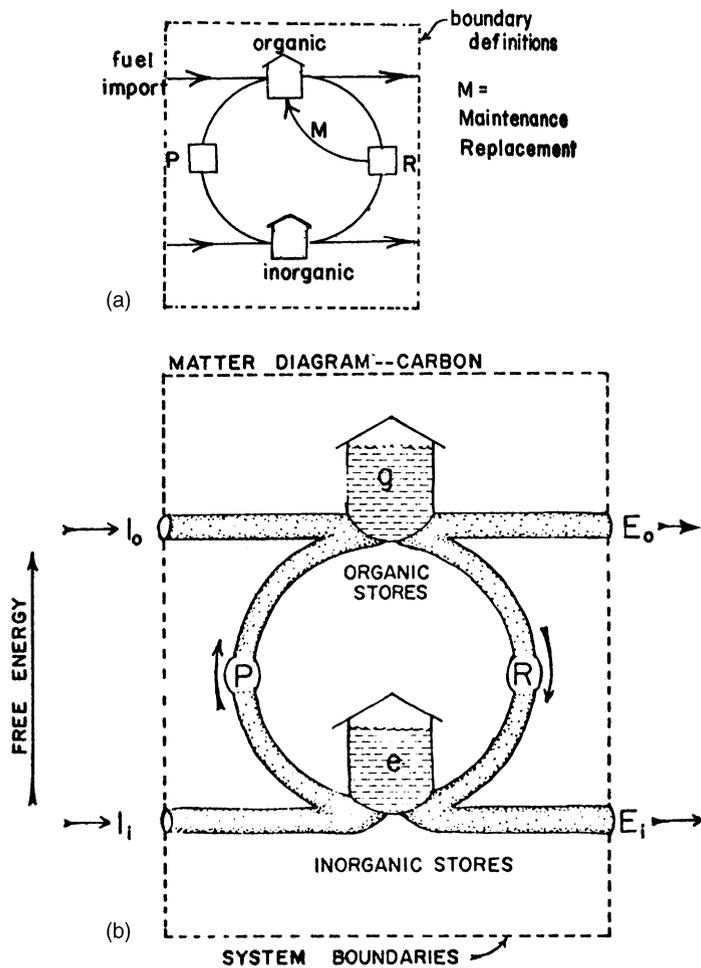


Fig. 4. (a) Diagram of boundary fluxes and system cycles of materials. House boxes represent storages (Odum, 1963a). (b) "Circuit diagram" of matter flow and storage.

of "imported fuel" cycling between organic and inorganic storages of carbon. The "house-like" symbols are the storages, while the boxes represent the processes of production and respiration. In this same paper, Odum revised his energy flow diagram in Fig. 1 to include a storage of organic matter (Fig. 5). In another paper this same year (which came first is difficult to tell) the diagram of boundary fluxes is given but with flows that resemble pipes, and storages that resemble water tanks (Odum, 1963b). It has been suggested that the storage symbol was inspired by the elevated public supply water tanks that supplied water pressure to the small cities dotting the Texas landscape.

A year later, in 1964, Odum reviewed a symposium volume on net production of terrestrial communities (Odum, 1964). In his review, he pointed out that the various authors were all measuring and discussing quite different fluxes under the same name and produced the systems diagram in Fig. 6 to illustrate the various definitions of net production. This diagram is the first published use of the storage symbol in a relatively complex array of energy flows, components, and processes. Also the hexagon symbol, to be used later for the "self-maintenance" or consumer was shown on its side and labeled respiration.

The first definition of an energy circuit language in the literature was in 1967 (Odum, 1967a). Odum il-

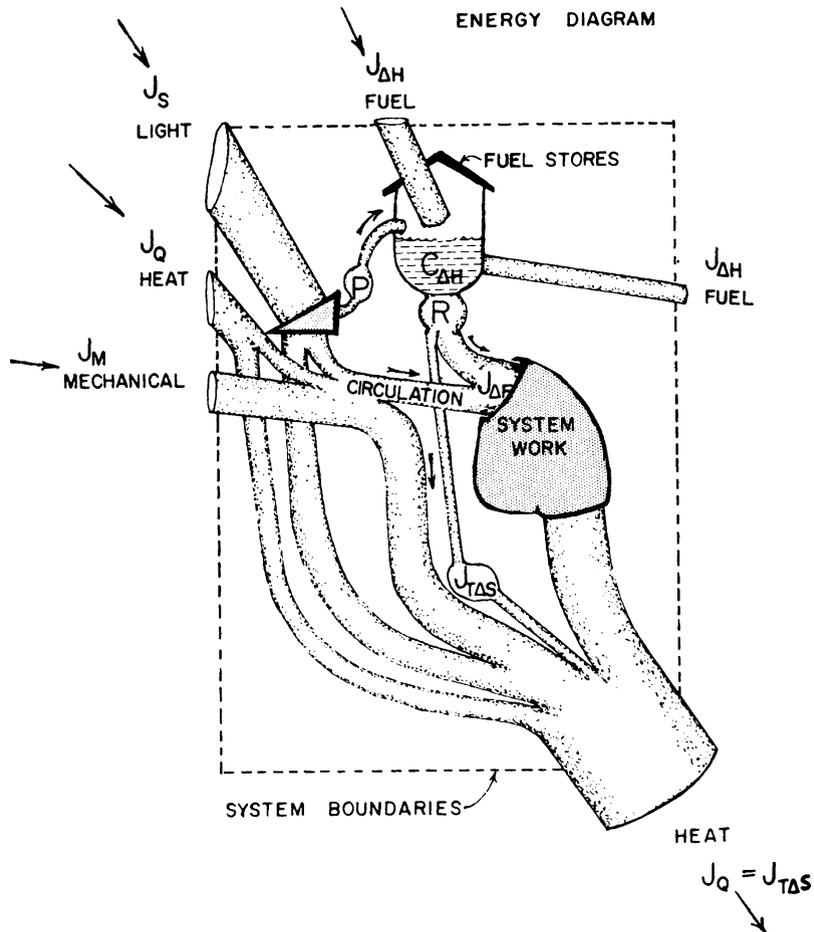


Fig. 5. Energy circuit diagram for an ecosystem showing the main input and output energy fluxes. P, gross primary production; R, total respiration; F, free energy; H, heat of reaction; S, entropy.

illustrated a paper devoted to analysis of the energetics of the world food problem with numerous "circuit diagrams" (Odum, 1967b). As a prelude to the diagrams he introduced and defined the symbols (Fig. 7). An example of one of the circuit diagrams (tribal cattle system in Uganda) is shown in Fig. 8. This was the first time that a diagram was evaluated and quantities were included on pathways and some compartments. Prior to this paper, Odum had not published circuit diagrams of any systems larger in scale or that included humans.

The publication of his book *Environment Power and Society* culminated a decade of development of the language (Odum, 1971). The energy circuit language

had emerged (Fig. 9), was explicitly defined, the mathematics illustrated and used extensively to explain in "pictures" what words often failed to do... that is to capture whole systems, their energetics, and dynamics. As Odum explained...

When systems are considered in energy terms, some of the bewildering complexity of our world disappears: situations of many types and sizes turn out to be special cases of relatively few basic types... Energy diagramming helps us consider the great problems of power, pollution, population, food, and war free from our fetters of indoctrination. (Odum, 1971)

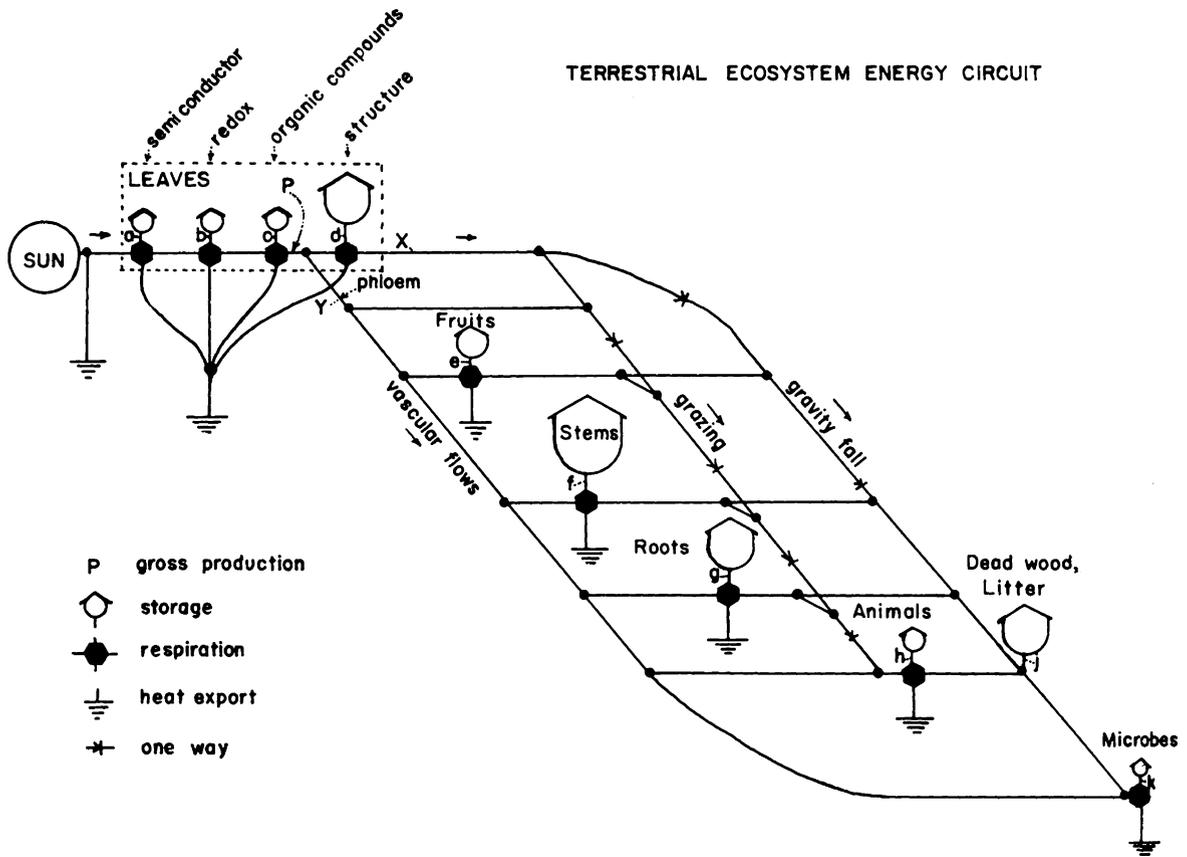


Fig. 6. Diagram illustrating various definitions of net production. Diagram includes the first use of the hexagon symbol and storage tank symbol which form is used until the mid-1970s.

Environment Power and Society contains a wealth of energy circuit diagrams¹ from diagrams of ecosystems, agriculture, economic systems, and political systems to diagrams depicting humans in relation to religion and religious control of society.

There seems to have been a watershed in the development of the language and Odum's use of simulation that occurred about 1971. With the publication of Environment Power and Society (Odum, 1971) and his move to the University of Florida, the language evolved rapidly, and his use of the language to describe and illustrate concepts and principles as well as the use of simulation seemed to increase exponentially. In the 12 years between 1971 and 1983 when

his book "Systems Ecology (Odum, 1983) was published, Odum authored over 80 papers, all of which contributed to developing and refining the syntax of the energy systems language².

In 1972, Odum contributed a chapter to an edited volume by Bernard Patten (Patten, 1972), titled "Energy Circuit Language for Ecological and Social Systems: Its Physical Basis" (Odum, 1972b) the chapter describes in detail the language and its use through illustrating many basic principles and equations of physics and chemistry. In addition to describing single symbols, Odum began here to mathematically combine symbols into basic "circuits" concentrating on

¹ Odum uses energy network, energy circuit, energy flow, and energy to describe diagrams in the text, somewhat interchangeably.

² It appears that Odum referred to the language as "energy circuit language" until after the publication of Systems Ecology in 1983. Some time in the mid 1980s he began referring to the language as "energy systems."

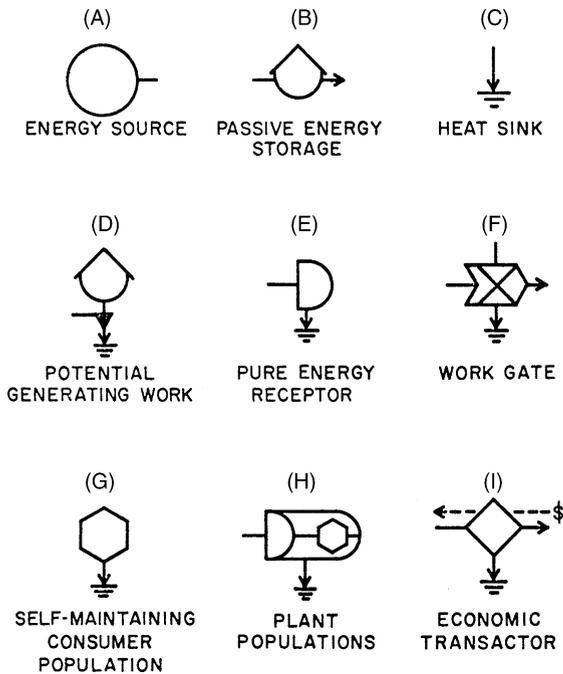


Fig. 7. Energy network symbols, c.1967.

“reward loops” and the cycling receptor, and to explore dynamic behavior.

During the early 1970s system diagrams become increasingly complex. It was nothing for diagrams to have dozens of compartments and processes, with lines traversing the page. Often publications reverted to fold out pages in order to accommodate gigantic diagrams summarizing everything believed important about one system or another. Even with this complexity, the diagrams held a measure of simplification that enabled the viewer to see the system, albeit complex. This trend was reversed in the mid 1970s with the publication of another chapter in a volume edited by Bernard Patten (1976). The volume was titled *Systems Analysis and Simulation in Ecology*; Odum’s chapter was titled “Macroscopic Minimodels of Man and Nature” (Odum, 1976). Odum introduced the chapter as follows:

“Man is embedded in a complex world of confusing cues threatening to overwhelm him psychologically as much as physically. His finest role in the mechanism of this planet may be to become its steersman—if he can learn to cut through the

plethora of detail his knowledge has brought and “see” the essence of man-nature interactions. Science is unlikely to help if it continues to focus on atoms and the short term.... The thesis here is that complexity must be reduced to essentials if complexity is to be overcome as an impediment to understand and correct action, and this means modeling. The specific tool envisioned is overview models that are macroscopic in viewpoint but minidimensional in complexity—“macroscopic minimodels”.... Just as an artist seeks to capture an impression of what he views, scientists also must find ways to suppress detail and formulate the subjective qualitative essence of facts and figures.”

In the mid 1970s Odum recognized that the Industrial Dynamics symbols³ developed by J. Forrester at MIT were being increasingly used to describe and program simulation models (Forrester, 1963, 1970). As a result, he published two papers where comparison of the energy systems symbols was made with those of Forrester’s dynamics symbols (Fig. 10) (see Odum, 1974, 1976). It was also at mid decade that two important developments occurred in the language. Both changed the look of diagrams, but one had more profound changes because it recognized a fundamental characteristic of a class of energy sources that were labeled “flow limited,” while the other changed the look of the symbols themselves because of Odum’s use of a “new technology.” The new technology was the use of templates for drawing energy systems diagrams. The templates were made of green plastic like the templates used by electrical engineers or architects when drawing electrical diagrams or house plans. It simplified all the symbols but probably the single most important was the fact that the overhanging “roofs of the birdhouse” symbol gave way to the tank symbol as shown in Fig. 11a. Hundreds of the templates were made in several different versions, that were given away freely to students, colleagues and conference goers around the world.

The more important development at mid decade resulted from the recognition that some energy sources have the characteristic of being independently limited but not constant forces. Instead they are “flow limited.” The sun’s energy streaming to planet earth

³ The prelude to the STELLA simulation package.

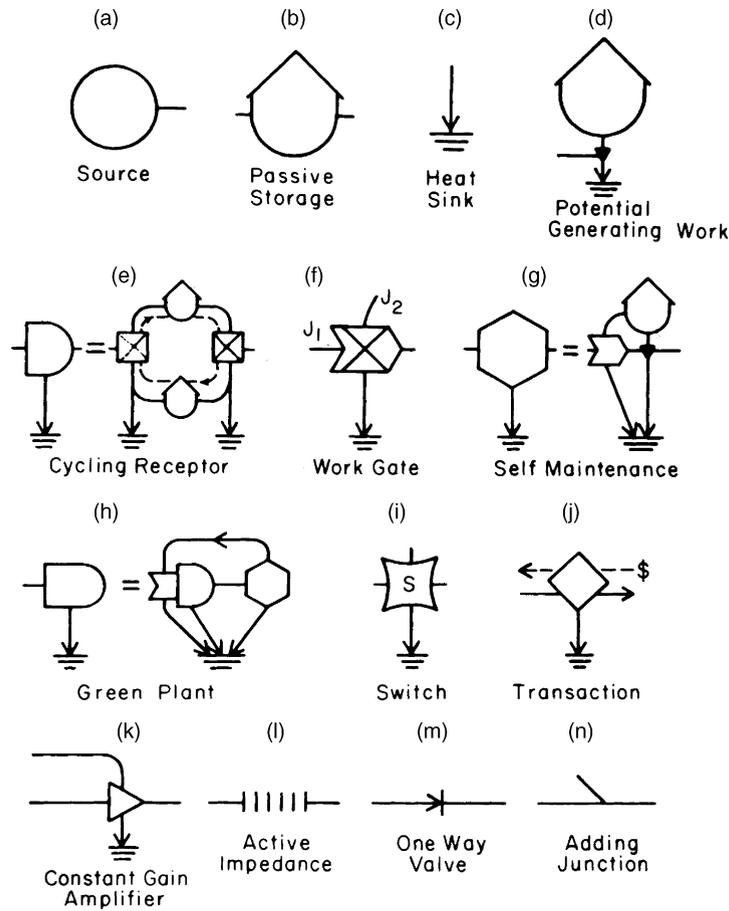


Fig. 9. Symbols of energy circuit language c.1970 (Odum, 1971).

tem but with fewer components that represented aggregates of components of similar functions and properties. Seldom were diagrams given in papers and texts without their accompanying simulation results. Fig. 12 is an example figure where diagram, equations and simulation results are included.

In about 1991, Odum “discovered” an iconic simulation program called EXTENDTM. Thus began a several year process of programming that led to development of the simulation blocks that could be connected with flow lines, numerical values entered into a dialog box to characterize the interactions between components, and then the program run (Fig. 13). Because of the proprietary nature of the underlying software, the simulation blocks have not been widely used. Prior to his death, Odum had been negotiating with the company that owned the software to allow release of a

very early version with his energy systems symbols, but the company balked at the idea of allowing early versions to circulate freely, even though they had long since released many updates. This dilemma illustrated one of Odum’s pet peeves... the fact that software companies continued to develop and release more and more complex versions of their programs requiring more and more computing power but the earlier versions worked just fine and were invariably simpler to use. While access to earlier versions continued to be restricted, Odum felt that if they were released they might increase productivity and the free flow of information globally.

The 1990s resulted in few if any changes to the language, although they were extremely significant regarding the development of simulation models and modeling in general and especially regarding the de-

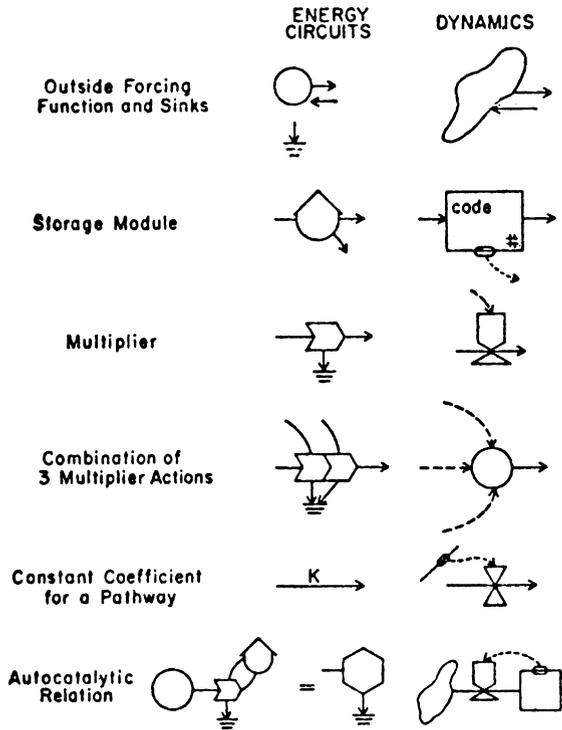


Fig. 10. Comparison of energy circuit symbols with the dynamic symbols of Forrester.

velopment of the energy theory. In the years between 1986 and 1990, The Cousteau Society provided funding and logistical support for evaluations of many global environmental issues. It was during this time that significant advances in the energy theory occurred. These advances found their way into the systems thinking and publications of the decade to follow. Of critical importance was Odum's book, *Environmental Accounting: Emery and Environmental Decision Making* (Odum, 1996). While the energy circuit language did not exhibit change in this book, several generic diagrams were offered as a means of summarizing the energy flows for nations.

In 1998 Odum suggested, as a major undertaking for the International Society of Ecological Modeling (Odum, 1998), that modelers represent their simulation models with energy systems diagrams.

In a project supervised by committee and with the participation and approval of the authors of each model, an atlas of diagrams of simulation models

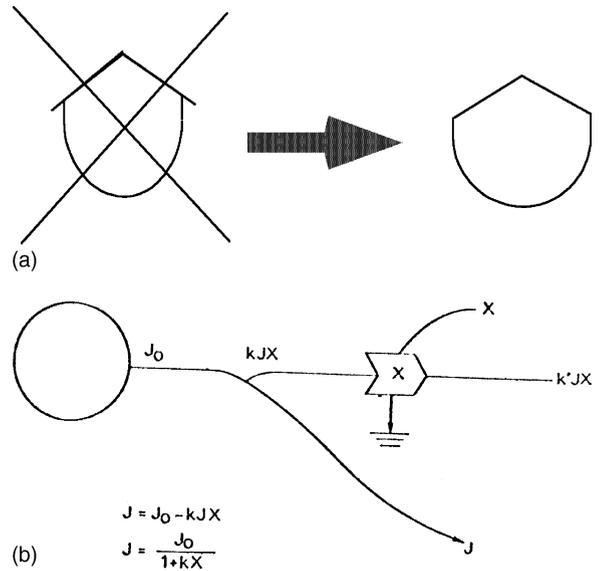


Fig. 11. In the mid 1970s two changes in the language occurred. (a) The storage symbol lost its overhang and (b) a fundamental principle of flow limited source was recognized resulting in a new symbol (the flow limited source).

can be prepared. Each diagram should be accompanied by the difference and logic equations extracted from the computer codes and also represented by the symbol network. making models visible and more easily understood will encourage use by more people, more discussion of the structure and functions in previous models and more building of one effort on another. people can trust a model better if they understand what is in it. then they can suggest the changes they require for additional use in other situations.

Like many of Odum's ideas the proposal seemed to fall on deaf ears, probably because, as so often was the case, it was way before its time.

In the late 1990s Odum increasingly used computer software to draw his diagrams. A library of symbols was developed, saved in numerous formats and freely distributed (<http://www.ees.ufl.edu/cep>). With the increased use of computer software Odum began to "experiment" with textures and shading as well as size of individual components to help make meaning more clear. His diagrams took on shades of gray and textural patterns that indicated concentration

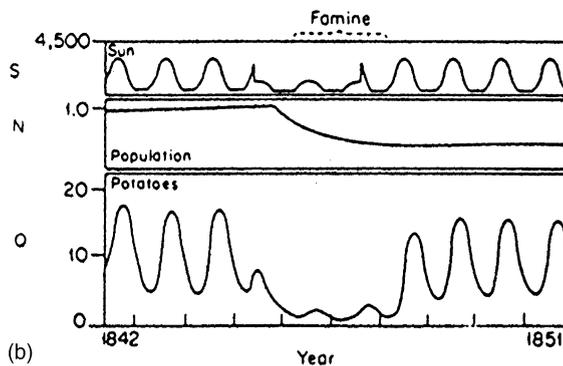
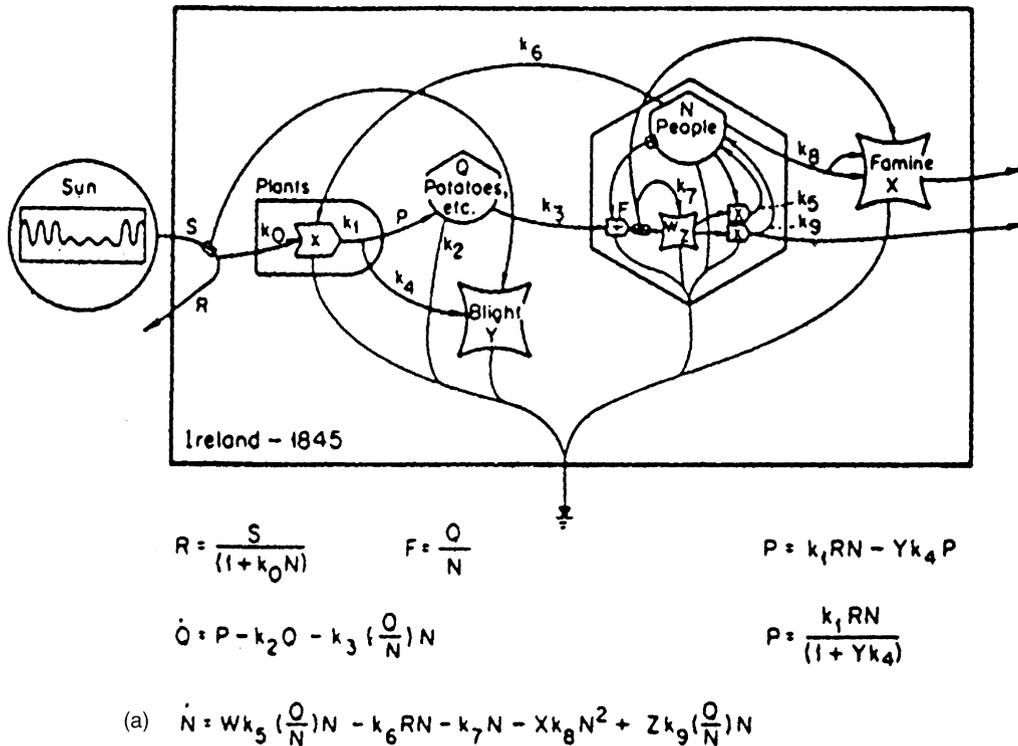


Fig. 12. Increasingly, in the 1990s Odum presented diagrams, equations and curves that resulted from the simulation of the models.

and difference between energy and material flows and storages. Varying the size of symbols indicated physical size of storages and/or their importance. The diagram in Fig. 14 (Odum, elsewhere in this volume) illustrates both changes in size and the use of patterns to show differences in concentration and relative number of components represented by each symbol.

5. Pictorial analogies

Odum often used pictures and analogy to make his points. One of the more interesting was his famous “cannon-ball catcher” analogy for green plant adaptations for maximizing power (Fig. 15) (Odum et al., 1958). The purpose of the analogy was “...to make clear the hypothesis that photosynthetic systems in-

Grass-food Chain v1 4 array

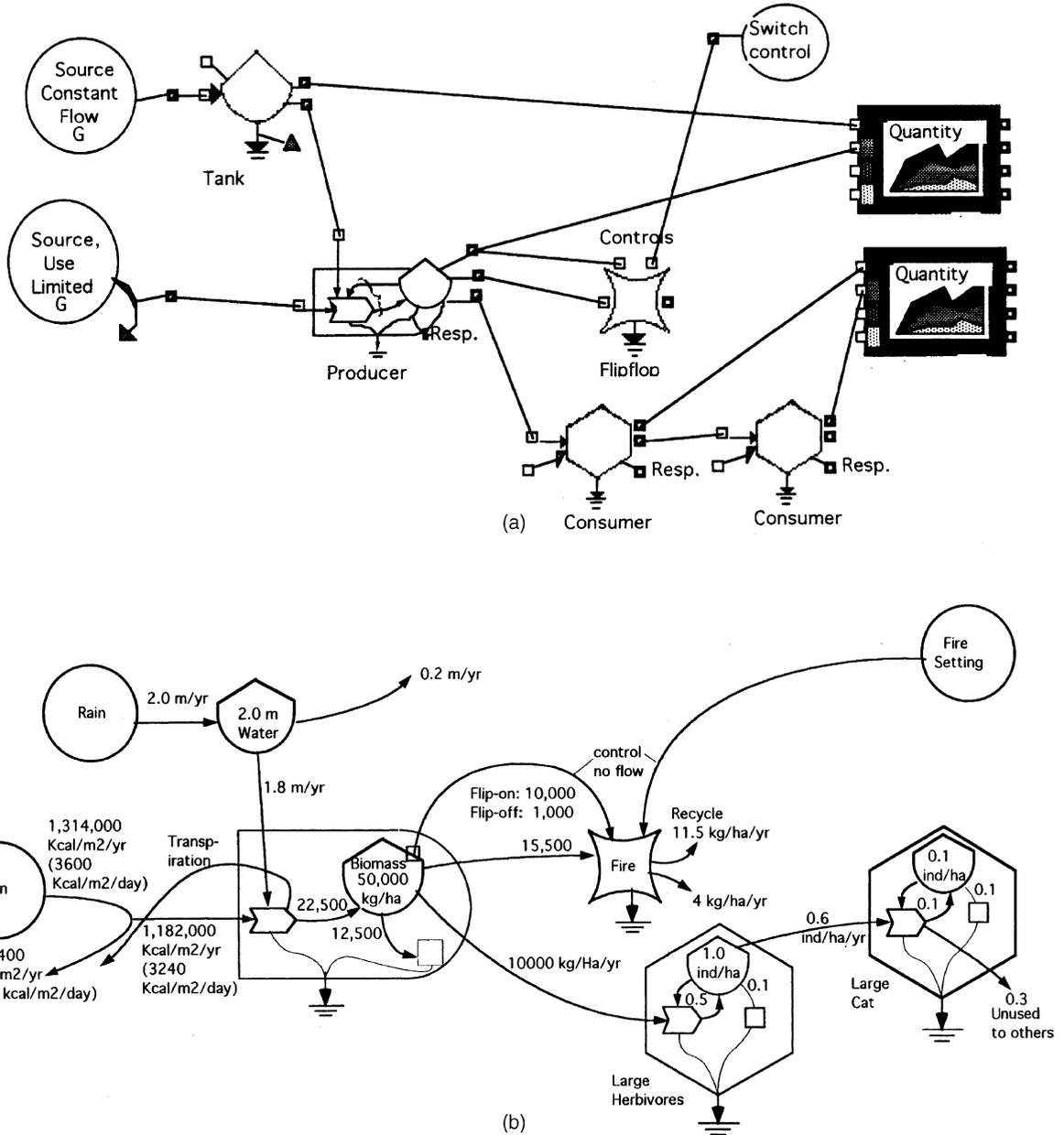


Fig. 13. (a) Systems diagram of a grassland foodchain for simulation using the iconic simulation program called EXTEND™. (b) The energy systems diagram of the same system with numerical evaluation of flows and storages.

der to maintain maximum power output can regulate the input power by regulating the chlorophyll.” The canon ball catcher was the gestalt for the “cycling receptor” As it developed the cycling receptor was the

basis for the kinetics of the green plant group symbol which was a combination of a cycling receptor and the self-maintenance symbol (see Fig. 9). As always, Odum’s thinking, combined with detailed field col-

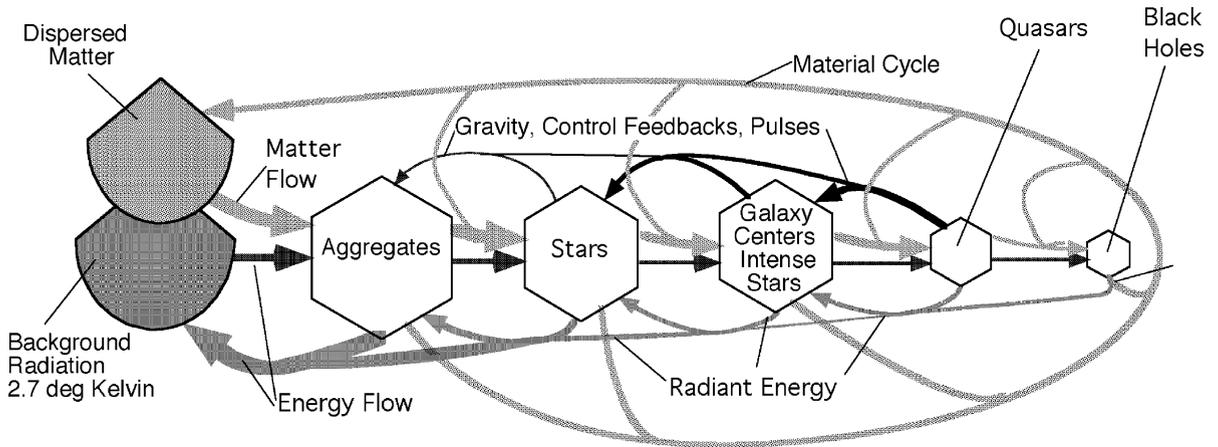


Fig. 14. The systems diagrams in the late 1990s took on a new look with the flexibility of computer software drawing programs. Odum often used texture and patterns to convey his meaning and materials and energy were often characterized using solid lines (energy and information) and patterns (materials). (Odum, this volume)

lected data and subsequent analysis, produced a theoretical construct, which was illustrated and understood using analogy and pictures which then reinforced the theory, eventually translating into modifications of the symbol language and its implied kinetics.

In a paper exploring the net energy of energy supplies supporting the USA economy (Odum et al.,

1976), Odum used a circular model of the economy with energy sources arranged around the outside contributing energy to keep the cycle going (Fig. 16). The pictorial analogy is one of a merry-go-round where each source is like a child pushing... some, because of their size or physical prowess can push harder, some drag more than they

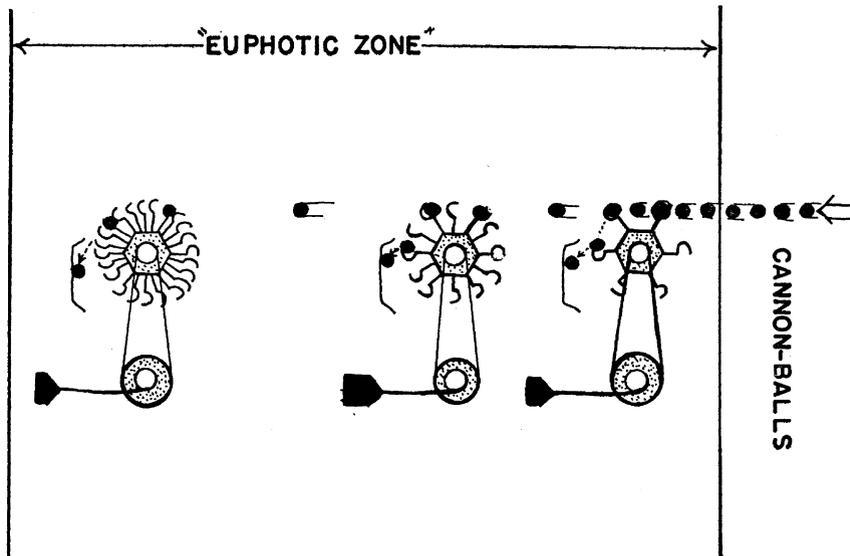


Fig. 15. The cannon-ball catcher; an example of Odum’s use of pictorial analogy. Successful photosynthetic systems have... “mechanisms to change the number of ‘cups’ in order to adapt to the rate of energy flux and so as to develop maximum power output of the entire population throughout the euphotic zone.”

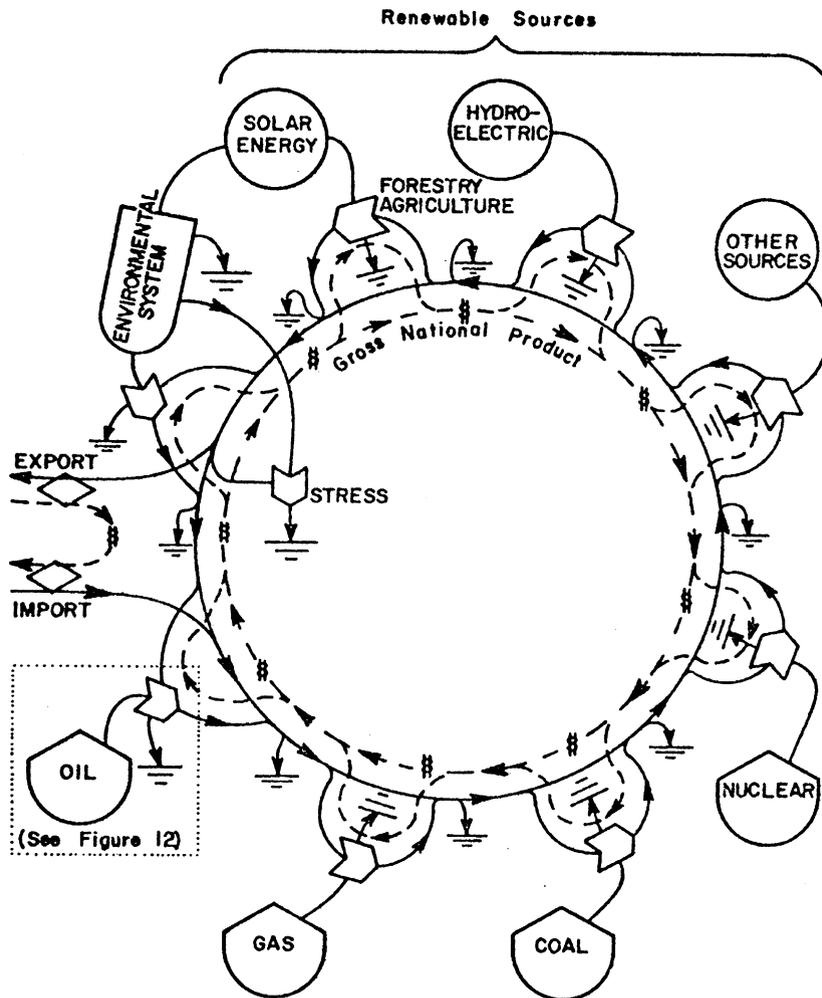


Fig. 16. The economy of a country shown as a circular wheel driven by its energy sources. the analogy was used to describe how different energies contribute differently to the overall economy of nations.

push. The diagram shows the money economy intimately connected to its energy flowing in the opposite direction.

Odum was probably his most creative when exploring realms outside his "normal" science (if there was such a thing). He often said that scientific progress came more readily when someone crossed disciplines and brought to the new discipline fresh ways of seeing unencumbered by the dogma of that discipline. Or to put it another way, "One of the principle ways in which science makes progress is through the imagination of people who get an idea from one phenomenon that suggests how another situation might be observed"

(Odum, 1960b). Fig. 17 is a systems diagram of the role of humans within the biosphere, drawn for a paper presented at Rollins College, in Florida, for a conference titled "The Ecosystem, Energy, and Human Values—The Next 100 years." The bottom sketch by Odum, shows the "real world example" which is in itself a pictorial analogy of the actual phenomena, while the top system diagram synthesizes the concepts into a concise analogy. The sketch and diagram illustrate "the role of humans as sensing, interpreting, and acting on the basis of simplified ideas and models generated to help the system gain an overview image of itself." (Odum, 1977)

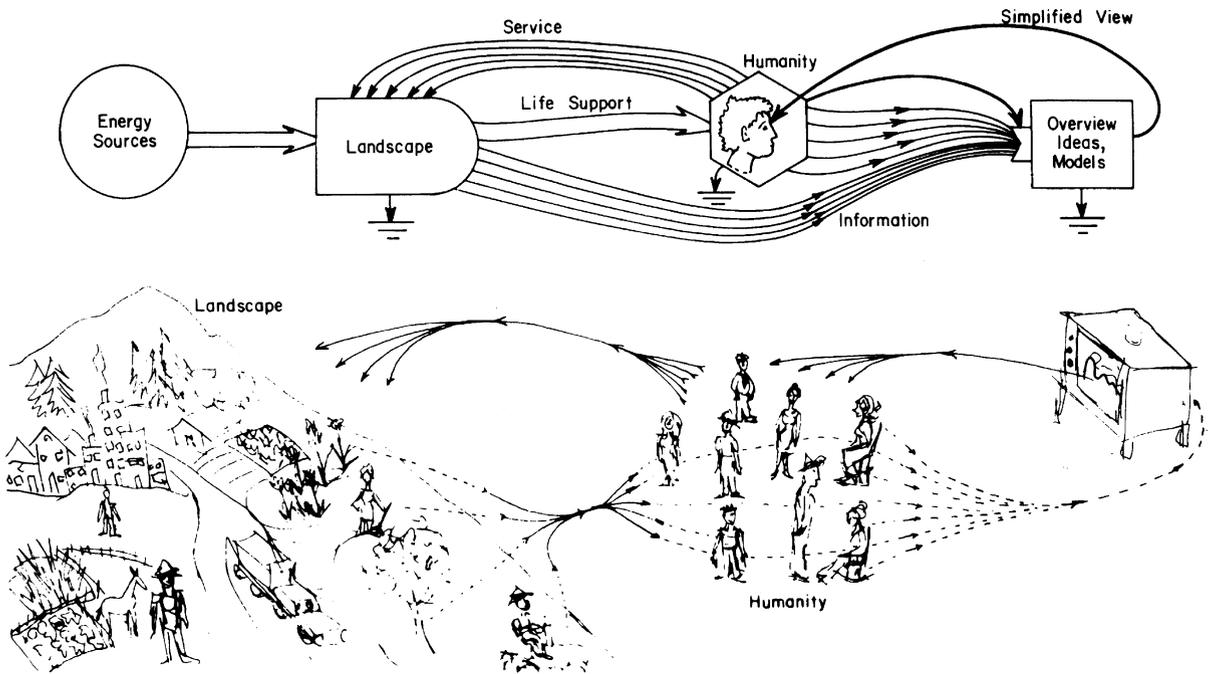


Fig. 17. Diagram and sketch illustrating humanity's role as good stewards of the environment. Odum often used sketches with his diagrams to get his point across.

6. Summary

In summary, I can think of no better way to summarize development of the energy circuit language than to quote Odum.

Everything and anything that takes place on earth involves a flow of potential energy, provided primarily from the sun, as it streams toward a pool of dispersed or expended heat. The pathways of the stream are shaped by a hierarchy of directive forces that have evolved under nature's laws as by-products of the stream. These directive forces include wayside storages of energy in the material patterns and dynamic circulations of the earth's substances, including all the elements of the biosphere from the earliest and most primitive to the latest and most civilized or spiritual elements of human feeling, thinking and behavior in the arts, sciences, and religions. . . .

The evolution of all events in the earth's history of thousands of millions of years is potentially explainable by, and hence can be said to be caused by, the operation of the total dynamic system accord-

ing to the laws which we today find operating. This is quite different from a common and mistaken interpretation of thermodynamic laws of only a few decades ago. Today it has become clear that the evolution of events in the cosmos is a prior totality out of which flow the evolution of the events we call biological and human. Man is not alien in, but a creature evolved in the service of, the dynamic flows of the surrounding world. (Odum, 1977)

Odum was convinced that the role of humans was to make clear, understanding of universal totality and man's place within it. . . . "man as the high-quality culmination of diffuse parts of the system [the universal totality] is the means by which the system visualizes an image of itself." (Odum, 1977). Since no system can understand itself, the way it can approach understanding is to develop simplified models which have enough of the characteristics of the original system to resemble reality, but at the same time are simple enough to be understood. Odum's energy circuit language is an extremely powerful method for humanity to help the system see and understand itself.

References

- Forrester, J., 1963. *Industrial Dynamics*. MIT Press, Cambridge, MA.
- Forrester, J., 1970. *Urban Dynamics*. MIT Press, Cambridge, MA.
- Odum, H.T., 1956. Primary production in flowing waters. *Limnol. Oceanogr.* 1, 102–117.
- Odum, H.T., 1958. Relationship of biology and the other sciences in teaching (pp. 16–24). In: *Proceedings of the Fifth Annual Conference for the Advancement of Science and Mathematics Teaching*. University of Texas, Austin, 122 pp.
- Odum, H.T., McConnell, W., Abbott, W., 1958. The chlorophyll-a of communities. *Publ. Inst. Mar. Sci. Univ. Tex.* 5, 65–96.
- Odum, H.T., 1960a. Ecological potential and analog circuits for the ecosystem. *Am. Sci.* 48, 1–8.
- Odum, H.T., 1960b. Ten classroom sessions in ecology. *Am. Biol. Teacher* 22, 71–78.
- Odum, H.T., 1962. The use of a network energy simulator to synthesize systems and develop analogous theory: the ecosystem example (pp. 291–297). In: *Proceedings of the Cullowhee Conference on Training in Biomathematics*. 390 pp.
- Odum, H.T., 1963a. Limits of remote ecosystems containing man. *Am. Biol. Teacher* 25, 429–443.
- Odum, H.T., 1963b. Paper presented at a working meeting held at the University of Texas January 30–February 1, US Atomic Energy Commission.
- Odum, H.T., 1964. A symposium on net production of terrestrial communities. *Rev. Ecol.* 45, 415–416.
- Odum, H.T., 1967a. Work circuits and system stress. In: Young, H.E. (Ed.), *Proceedings of the Symposium on Primary Productivity and Mineral Cycling in Natural Ecosystems*, University of Maine Press, pp. 81–138.
- Odum, H.T., 1967b. Energetics of food production. In: *The World Food Problem, Report of the President's Science Advisory Committee, Panel on World Food Supply*, vol. 3. The Whitehouse, pp. 55–94.
- Odum, H.T., 1971. *Environment, Power and Society*. Wiley, New York, 336 pp.
- Odum, H.T., 1972a. Use of energy diagrams for environmental impact statements. In: *Tools for Coastal Management. Proceedings of the Conference February 14–15, 1972*, Marine Technology Society, Washington DC, pp. 197–213.
- Odum, H.T., 1972b. An energy circuit language for ecological and social systems: its physical basis. In: Patten, B. (Ed.), *Systems Analysis and Simulation in Ecology*, vol. 2. Academic Press, New York. pp. 139–211.
- Odum, H.T., 1974. Marine ecosystems with energy circuit diagrams. In: Nihoul, J.C.J. (Ed.), *Modelling of Marine Systems*, Elsevier Oceanography Series, Elsevier Scientific Publishing Co., NY, pp. 127–151.
- Odum, H.T., 1975a. Implications of Energy Use on Environmental Conservation and Future Ways of Life. Preprints UNESCO Conference in Zaire, Africa, 20 pp.
- Odum, H.T., 1975b. Combining energy laws and corollaries of the maximum power principle with visual systems mathematics. In: *Ecosystem Analysis and Prediction. Proceedings of the Conference on Ecosystems*, SIAM Institute for Mathematics and Society, Alta, Utah, pp. 239–263.
- Odum, H.T., 1976. Macroscopic minimodels for balance of man and nature. In: Patten, B. (Ed.), *Systems Analysis and Simulation in Ecology*, vol. 4. Academic Press, New York, pp. 250–280.
- Odum, H.T., et al., 1976. Net energy analysis of alternatives for the United States. In: *U.S. Energy Policy: Trends and Goals. Part V—Middle and Long-term Energy Policies and Alternatives. Proceedings of the 94th Congress Second Session Committee Print. Prepared for the Subcommittee on Energy and Power of the Committee on Interstate and Foreign Commerce of the U.S. House of Representatives, 66-723*, U.S. Govt. Printing Office, Washington, DC, pp. 254–304.
- Odum, H.T., 1977. The ecosystem, energy and human values. *Zygon* 12, 109–133.
- Odum, H.T., 1983. *Systems Ecology: An Introduction*. Wiley, New York, 644 pp.
- Odum, H.T., 1994. *Ecological and General Systems: An Introduction to Systems Ecology*. (Revised edition of *Systems Ecology*, 1983, Wiley, New York, 644 pp.) University Press of Colorado, Niwot, CO, 644 pp.
- Odum, H.T., 1995. Energy systems and the unification of sciences (pp. 365–373). In: Hall, C.A.S. (Ed.), *Maximum Power* (Festschrift of 1989 H.T. Odum celebration at the University of NC). University Press of Colorado, Niwot, 393 pp.
- Odum, H.T., 1996. *Environmental Accounting: EMERGY and Decision Making*. Wiley, New York, 370 pp.
- Odum, H.T., 1998. Suggestion for a project for the International Society for Ecological Modelling: representing simulation models with energy systems (pp. 1–11). In: *Ecomod, Newsletter of International Society for Ecological Modelling*, December 1998.
- Odum, H.T., Odum, E.C., 2000. *Modeling for All Scales, an Introduction to System Simulation*. Academic Press, San Diego, CA, 458 pp. With computer simulation disk.
- Patten, B., (Ed.), 1972. *Systems Analysis and Simulation in Ecology*, vol. 2. Academic Press, New York.
- Patten, B., (Ed.), 1976. *Systems Analysis and Simulation in Ecology*, vol. 4. Academic Press, New York.