Springer Environmental Science and Engineering

Kampeng Lei
Shaoqi Zhou
Zhishi Wang

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Science Press
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Kampeng Lei · Shaoqi Zhou · Zhishi Wang

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(有限系统的生态能量核算

——基本原理和案例研究)

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Kampeng Lei
Macau Science and Technology Association
Macao, People's Republic of China

Shaoqi Zhou
College of Environment and Energy
South China University of Technology
Guangzhou, People's Republic of China
and
Guizhou Academy of Sciences
Guiyang, People's Republic of China

Zhishi Wang
Faculty of Science and Technology
The University of Macau
Macao, People's Republic of China

ISSN 2194-3214
ISSN 2194-3222 (electronic)
ISBN 978-3-642-45169-0
ISBN 978-3-642-45170-6 (eBook)
DOI 10.1007/978-3-642-45170-6
Springer Heidelberg New York Dordrecht London

Jointly published with Science Press, Beijing
ISBN: 978-7-03-038271-9 Science Press, Beijing

Library of Congress Control Number: 2013958393

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Ecological Emergy Accounting for a Limited System: General Principles and a Case Study of Macao

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Preface

In December 2000, the conference "New Challenge of Eco-city Development in 21st Century" was held in Macao by the Ecological Society of China. At this conference, one of us (Lei) first encountered the theory of ecological economics. Since then, Lei has become increasingly concerned about the sustainability of his home city, Macao. Macao is a city with a dense population that depends heavily on exogenous natural resources, but benefits greatly from the gambling and tourism income that flows into the city. Residents benefit greatly from the high net influx of materials and energy into Macao, and as a result of these inflows, the standard of living of the citizens has steadily increased during the past 30 years.

However, there are concerns over whether the city's rapid development is sustainable. Sustainable development combines concerns about the carrying capacity of the natural systems that sustain human systems with concerns about the social challenges faced by humanity, and particularly the need for socioeconomic development. For development to be sustainable, it must meet the needs both of humans and of the natural environment. To study Macao's sustainability, it was necessary to choose an approach and a system of metrics that could relate the natural environment's flows to those of the socioeconomic system. Based on a careful review of the literature, Lei chose emergy synthesis. Emergy synthesis measures the flows of materials, energy, commodities, money, and services, and can easily quantify these values within a common analytical framework that integrates all the flows and allows direct comparisons among them. The clear advantage of emergy synthesis is that it combines the most insightful features of the ecological and economic methods of analysis, thereby providing a complete picture of the human and environmental meaning of the flows.

In this book, we have used the emergy synthesis approach to develop an accounting model that is suitable for describing systems with relatively clear boundaries, such as an urban system, thereby providing a comprehensive picture of the system. Our book has eight chapters, and is organized as follows:

Chapter 1 gives a general introduction to the basic theoretical background for emergy accounting and related fields, and defines many of the key parameters and indicators used in emergy studies.

Chapter 2 first presents a detailed emergy accounting for Macao in 2004, followed by a time series of the emergy flows in Macao's system from 1983 to 2004 and a comparison with Italy and Sweden to put these values in perspective. Finally, we present a statistical analysis of Macao's emergy-based indicators.

Chapter 3 presents the results of simulating Macao's system using the STELLA dynamic modeling software to investigate and characterize the evolution and development of Macao's natural and socioeconomic systems from 1983 to 2003. Based on the simulation results, we also predict the evolution of these systems in the coming 20 years and its relationship with the ongoing land reclamation from the sea that is occurring in Macao.

Chapter 4 focuses on an emergy accounting for the city's tourism industry. First, we introduce the historical evolution and economic contributions of the tourism industry, followed by a detailed emergy calculation and assessment of its contributions and impacts from 1983 to 2004. Finally, we determine the net emergy for Macao's tourism industry and draw conclusions about this sector's impacts.

In Chap. 5, we analyze the emergy flows in the gambling sector. Gambling and related tourism activities represent a special form of economic and societal activity, and have been crucial to Macao's success.

Chapter 6 describes a detailed emergy accounting of waste treatment in Macao, including some pioneering efforts to include previously neglected flows such as gaseous emissions. We describe the related feedback ratios for solid wastes, sewage, and gaseous emissions and use the results to determine the efficiency of Macao's waste treatment and calculate the transformities of these wastes using Macao's waste discharge data.

Chapter 7 shows how a comparison of the carrying capacity of a city's or a region's natural resources with the consumption of these resources at regional or global scales can reveal the system's sustainability. To illustrate how this comparison works in practice, we performed a case study of 17 representative countries, using data obtained from the National Environmental Accounting Database, and the results confirmed that to ensure long-term sustainability, it will be necessary to control population increases, reduce emergy consumption, and promote emergy efficiency.

Chapter 8 provides a final summary of the previous chapters, and identifies problems that will require additional research, as well as some shortcomings of the ecological energy accounting approach. It concludes with a research outlook for future researchers.

This book is intended for readers who want to learn more about how hybrid natural and socioeconomic systems function. This includes researchers and graduate students working in the fields of systems ecology, energy accounting, environmental management, and related areas. Readers will obtain a comprehensive understanding of the methodology of emergy synthesis, and of the dilemmas that government planners face as a result of the need to sustain socioeconomic development while protecting the environment, which will ultimately lead to sustainable socioeconomic development. We hope that by making this book available to students and researchers, we will promote the development of emergy analysis skills and increase knowledge of the importance of ecological energy accounting. We also hope that readers will be motivated to find ways to improve on the methods we describe in this book.

We gratefully acknowledge the assistance of Professor S. L. Huang of "National" Taipei University, Dr. H. F. Lu of the South China Botanical Garden of the Chinese Academy of Sciences, and Professor S. Ulgiati of Parthenope University of Napoli, Italy, for their constructive criticism of and comments on early versions of our manuscripts. We are also grateful for the efforts of the anonymous journal reviewers who rigorously critiqued the journal manuscripts that form the basis for the chapters of this book. We also gratefully acknowledge the assistance of Dr. S. Sweeney of the University of Florida, Gainesville, for providing the basic National Environmental Accounting Database data used in our technical analysis in Chap. 7, and for answering our questions about some categories in the calculations.

We thank the University of Macau, the South China University of Technology and the Guizhou Academy of Sciences for providing us with access to their rich research resources and with helpful support in many areas during our research and during the writing of this book. During the past 10 years we have received much professional and personal support and encouragement from people who are too numerous to list here. We thank all of them.

We are grateful for the financial support for our research from the Science and Technology Development Fund of Macau (grant 022/2007/A2), Macao Special Administrative Region, China; from the State Key Laboratory of Subtropical Building Sciences, South China University of Technology (grant 2012ZB06, 2013ZC03); the National Natural Science Foundation (21277052); and from the University of Macau. We also thank the Macao Foundation for sponsoring our publication.

Macau, China
Guangzhou, China

Kampeng Lei
Shaoqi Zhou
Zhishi Wang

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Chapter 1
Emergy Synthesis and Ecological Energy Accounting

To understand how emergy accounting can be used to study systems composed of both natural and human components, it is helpful to understand the evolution of the thought processes that led to this approach. In the first part of this chapter, we have summarized this evolution based on general overviews of systems theory (Wikipedia 2012a) and emergy (Wikipedia 2012b), supplemented by a consideration of the key papers that guided the development of this field of research. In the remainder of the chapter, we will develop the key equations and indicators used in this analytical approach and introduce how they can be used in a consideration of a hybrid natural/human system such as Macao's tourism economy.

Note: Because of the large number of parameters defined in this book, we have provided a summary of all parameters and their definitions in Appendix C.

1.1 The Evolution from Systems Theory to Emergy

During the last half of the 20th century, a dramatic change in our world view occurred: researchers in a range of fields began to recognize that many systems could not be understood by examining their component parts in isolation. Von Bertalanffy (1972) codified this recognition by defining a system as a set of interrelated elements that interact with each other and with the environment external to the system. The most important innovation of systems thinking is the shift from a focus on breaking a system into its component parts (an approach known as *reductionism*) to a focus on the system as a whole. This approach evolved from a growing understanding that living systems are integrated wholes, with properties that cannot be understood solely by examining the component parts. Howard Odum (1994a) noted that a system can no longer function as a system when its elements are taken apart and isolated.

Systems theory evolved as an attempt to unify the approaches of sciences that had formerly worked in isolation, thereby combining their strengths and unique insights to provide a more holistic view of a system. Systems theory focuses on complexity, interdependence, and wholeness (H. T. Odum 1994b). Although the science of ecology had always emphasized the *system* part of the word *ecosystem*, the new emphasis on system-based thinking reminded researchers who had adopted an increasingly narrow focus on individual components or processes to take a step back and examine how all these parts fit together. Odum was a leader in the development of the new approach to systems ecology. He defined systems ecology (H. T. Odum 1994a) as the study of a whole ecosystem by both measuring its overall behavior and studying the details of how that behavior emerges from interactions among the system's components. Odum also broadened the concept of an ecosystem to include all systems, including human systems; this is a key principle underlying the present book because it recognizes that no human system exists independently of the natural world, and that since the industrial revolution, the natural world has increasingly been affected by human systems. Systems ecology attempts to quantify the flows of energy, materials, and information within a system and between the system and its external environment. Odum envisioned systems ecology as a unifying theory that would be capable of consolidating our understanding of a wide range of quantitatively and qualitatively different systems. J. Björklund (2000) summarized the five key principles of systems ecology that Odum discussed in papers published between 1987 and 1996:

- The maximum empower principle: Systems self-organize to maximize their intake of energy and the efficiency of their use of this energy (H. T. Odum 1995). The maximum empower principle is a potential guide to understanding the patterns and processes of ecosystem development and sustainability. The principle predicts the selective persistence of ecosystem designs that can capture a previously untapped energy source (Cai et al. 2006).
- Self-organization principle: Self-organization is a process where some form of global order or coordination arises out of the local interactions between the components of an initially disordered system. A self-organizing system is typically very robust and able to survive and self-repair even substantial damage and to recover from even moderately severe perturbations. Self-organization generally requires feedbacks in which part of its high-quality energy is recycled and returned to upstream processes. Self-organization occurs in a variety of physical, chemical, biological, social, and cognitive systems.
- Energy transformation hierarchy: Different forms of energy have different levels of "quality"; here, *quality* refers to how efficiently energy can be used (i.e., the output of energy divided by the input) and to its suitability for a specific use.
- A theory of *pulsing*: Odum proposed that all systems pulse, on all scales. That is, the gradual accumulation of energy by a storage component of the system is followed by a short period of consumption of this energy and either modification of existing components or development of new components, leading to dispersion of materials and setting up of the next growth period.
- Phenomena occur at different spatial, temporal, and ecological scales: Although the overall processes that govern how a system functions will be similar at all scales, the details will vary among scales.

Howard Odum (1994a, 1995) referred to these points as "design" principles because they appear to be general properties of all systems, irrespective of their scale.

They are important because the existence of similar patterns at all scales provides a unified basis for modeling any ecological system.

All forms of systems theory emphasize a *holistic* world view. This means that the properties of a system cannot be determined or explained solely as the sum of its components. In contrast, advocates of *reductionism* believe that complex phenomena such as ecological systems can be reduced into their component parts and understood by examining the details of these components. In practice, both approaches are necessary: reductionism provides an understanding of the details of specific flows, allowing researchers to accurately quantify those flows, whereas the holistic approach lets researchers combine those quantities to provide an overall picture of the system.

Ecosystems provide *services* that are essential for human survival. Some of these services are natural (e.g., clean air) whereas others are artificial (e.g., mining to obtain raw materials), and some are highly concrete (e.g., clean water) whereas others are more abstract (e.g., scenic beauty). The *ecological footprint* concept attempts to quantify how human requirements for these services affect the system that provides them (Rees and Wackernagel 1996; Wackernagel and Rees 1996; Wackernagel and Yount 1998; Brown et al. 2000b).

Furthermore, Odum's model builds on *ecological energetics* (the balance between production and consumption) by explicitly measuring the integrated ecological and economic welfare of a system. This concept of ecological energetics was originally proposed by Phillipson (1966). Ecological energetics quantifies the flows of energy through ecological systems, with the goal of revealing the principles that describe the intensity of such energy flows through the trophic levels of an ecosystem. This approach is sometimes referred to as *production ecology*, because ecologists use the word *production* to describe the process of energy input and storage in *ecosystems*.

Ecological energetics provides information on the *interdependence* of organisms within ecological systems and on the efficiency of energy transfers within and between organisms and trophic levels. In a natural ecosystem, nearly all of the energy enters the system when plants (autotrophs) capture the sun's light energy and transform it into chemical energy through photosynthesis (*primary production*). This energy is used by plants to power their metabolism, and by animals that consume the plants to sustain their life, growth, and reproduction. This metabolic use of the energy captured by plants is termed *secondary production*. As energy passes through the trophic levels in the food chain (from plants to herbivores, from herbivores to carnivores, and finally, from both herbivores and carnivores to decomposers), the energy performs work and in the process is degraded into heat. In a closed system, the laws of thermodynamics state that the total light energy captured by plants will equal the sum of the energy used by the plants for their growth and metabolism, the energy transferred to other organisms, and losses of energy as heat. In practice, ecosystems are not truly closed (i.e., they always exchange energy or materials with their external environment), so energy is gained or lost when matter is (respectively) transferred into and out of the system. A system's energy budget quantifies all the pools of stored energy, and the directions and magnitudes of the energy flows between pools.

Ecology and economics are both disciplines that address complex systems, but have traditionally worked in isolation from each other. Although traditional economics focuses on the efficient allocation of resources, and should therefore include natural resources and ecosystem services, it has mostly ignored these aspects of economic problems. The result has often been actions and ecological policies that neglect either the natural or the human part of a hybrid human/natural system, often with disastrous consequences. The discipline of *ecological economics* attempts to adapt traditional economics so that it accounts for the interdependence and coevolution between human economies and natural ecosystems. The objective is to integrate the natural environment with economic thinking so that both the human and the natural components of the system are adequately accounted for. This combines the goal of improved human well-being through socioeconomic development with the goal of sustainable use of the services provided by ecosystems. This philosophy explicitly unites the human components of a system with the natural components that sustain them, and explicitly accounts for the effects of each component on the other components.

The theoretical and conceptual basis for the emergy methodology is grounded in a consideration of thermodynamics within the context of systems ecology (H. T. Odum 1983). Odum's early investigations of the energy flows in ecosystems and of the differences in the ability of sunlight, water currents, wind, and fossil fuels to do work made it clear that different forms of energy have different quality levels. This was first formally addressed in Odum's book *Environment, Power and Society* (H. T. Odum 1971). The lack of direct comparability between energy with different qualities makes it impossible to combine the flows of energy by means of simple addition. Odum therefore developed the concept of a need for a common denominator for energy, which he originally named the *energy cost*.

Energy can be expressed in many units (e.g., kcal, Btu, kW · h) ($1\ \text{Btu} = 1.05506 \times 10^3\ \text{J}$), but these units cannot communicate the *quality* of the energy. The ability of energy to do work depends on its quality, not just on its quantity, and a large amount of energy of a lower quality is required to create energy of a higher quality. In a sense, quality reflects how concentrated energy is and how easy it is to use; thus, it is analogous to energy density. The energy with the lowest quality is sunlight, and the quality increases as the solar energy is transformed into plant matter, coal, and oil, with electricity and information representing the highest qualities of energy.

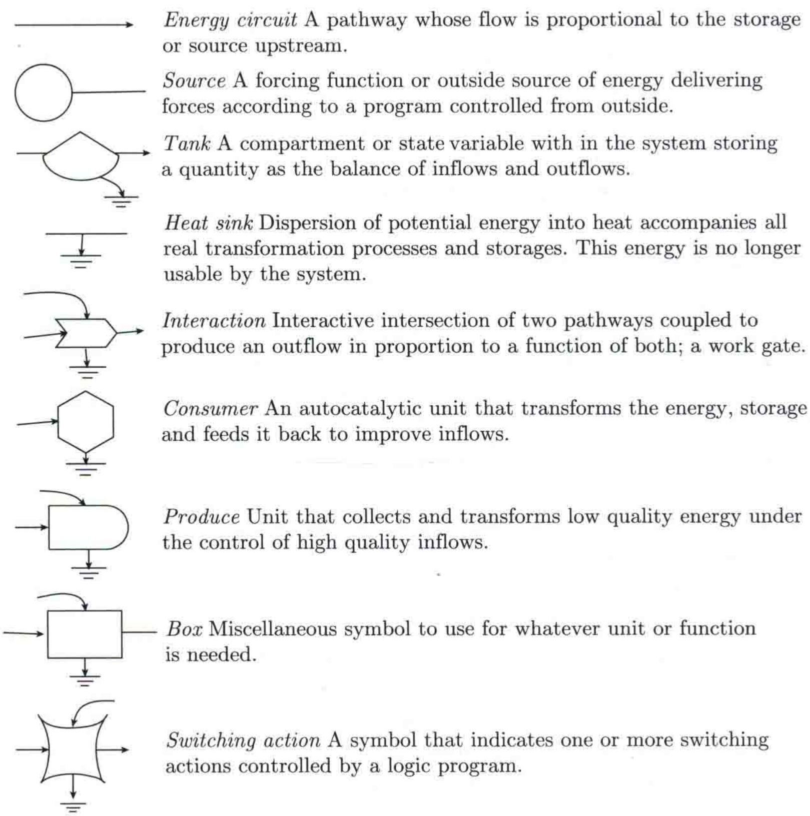
The first quantitative evaluation of energy quality appears to have been in Odum's 1975 speech when he accepted a prize from the Institut de la Vie, Paris, in which he presented a table of "energy quality factors". These represented the amount of solar energy (in kcal) required to create 1 kcal of energy with a higher quality (H. T. Odum 1976). This introduced the concept of an energy hierarchy, in which energy quality changes during the transformations from one type of energy to the next. Initially, the equivalence among types of energy with different qualities was expressed in *fossil fuel work equivalents*, with a rough equivalence between 1 kcal of fossil fuel and 2000 kcal of sunlight. *Energy quality ratios* were calculated by computing the quantity of energy consumed during the transformation of one type of energy into another type. These ratios could therefore be used to convert different forms of energy into a common set of units that allowed direct comparisons and direct addition of flows of different types of energy. The concept of fossil fuel work equivalents was replaced with *standard coal equivalents* in recognition of the fact that not all fossil fuels have equally high quality, then the quality evaluation system was converted into a solar energy basis, with the energy units termed *solar equivalents* (H. T. Odum 1977), in recognition of the crucial role of the sun in providing the energy for all natural systems.

The term *embodied energy* was used for the first time in the early 1980s to refer to energy quality differences (e.g., E. C. Odum and Odum 1980). However, since this term was being used by other researchers who were evaluating the fossil fuel energy required to generate various products, and these researchers neither included all forms of energy nor used the concept to account for differences in energy quality, ecological researchers developed the term *embodied solar calories* and defined the conversion factors between types of energy as *transformation ratios*. "Embodied energy" was abandoned altogether in 1986, when David Scienceman proposed the term *emergy* and the use of *emjoules* as the units of measurement to distinguish emergy units from the units of available energy (Scienceman 1987). The term *transformation ratio* was shortened to *transformity* around that time. It is important to note the shift that occurred throughout this period from fossil fuels to solar energy.

Since this early research, the theoretical and practical bases for emergy accounting have slowly matured, accompanied by standardization of the terminology and calculation methods. In the rest of this chapter, we will describe that terminology and the methodology.

1.2 Energy System Diagrams

The energy systems diagrams developed by Odum can be used to clarify the flows of energy among the components of a system (Fig. 1.1). Figure 1.2 illustrates the pathways (flows) and conservation of energy within a typical system. The key aspects of any system include flows of energy into and out of the system, transformation of energy and its storage in various pools within the system, consumption of energy by a process to do work, and flows of energy between storage pools. The laws of thermodynamics also suggest that there will inevitably be a loss of energy during storage, transformation, and flows between pools. In Odum's diagrams, energy of low quality enters the system on the left side, and as the energy flows towards the right side of the diagram, its quality increases through feedback loops within the system. These *autocatalytic loops* are a prevalent design because they reinforce power intake and efficient use, following the maximum empower principle (Brown 2003).



Energy circuit A pathway whose flow is proportional to the storage or source upstream.

Source A forcing function or outside source of energy delivering forces according to a program controlled from outside.

Tank A compartment or state variable with in the system storing a quantity as the balance of inflows and outflows.

Heat sink Dispersion of potential energy into heat accompanies all real transformation processes and storages. This energy is no longer usable by the system.

Interaction Interactive intersection of two pathways coupled to produce an outflow in proportion to a function of both; a work gate.

Consumer An autocatalytic unit that transforms the energy, storage and feeds it back to improve inflows.

Produce Unit that collects and transforms low quality energy under the control of high quality inflows.

Box Miscellaneous symbol to use for whatever unit or function is needed.

Switching action A symbol that indicates one or more switching actions controlled by a logic program.

Fig. 1.1 Primary symbols used in the energy systems diagrams developed by Odum

1.3 Emergy Values and Their Transformation

Emergy is the amount of energy required to produce something, and accounts for the conservation and loss of energy that result from the laws of thermodynamics (Scienceman 1987). The more work that is done to produce something, the more energy must be transformed to perform that work, and the higher the emergy value stored in the product. Emergy therefore measures the environmental work, in both the past and the present, that is necessary to produce a given resource or provide a given service. It is therefore a global measure of the sum of the energy flows in the processes required to produce something, expressed in consistent units of solar emergy (Fig. 1.3).

This method is grounded in thermodynamics and general systems theory (Bakshi 2002). Since all driving processes that support the biosphere (the sun, Earth's deep heat, tidal energy, and the energy of wind and rain) are incorporated in this framework, emergy evaluation accounts for all of the processes and resources required to support a system (Herendeen 2004).