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Ecology and Economy: Emergy Synthesis and Public Policy in Taiwan

Shu-Li Huang

Graduate Institute of Urban Planning, National Chung-Hsing University, Taipei, Taiwan 10433, Republic of China

and Howard T. Odum

Department of Environmental Engineering Sciences, University of Florida, Gainesville, Florida 32611, U.S.A.

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The "willingness-to-pay" based approach has been practiced by the neoclassical-oriented environmental economists to shadow price the value of natural environment, which has also been criticized by ecologists as a subjective approach and for lack of the biophysical value basis. This paper presents the methodology of emergy (spelled with an m) synthesis which emphasizes the use of energy as evaluating criteria for threading together natural systems and human economy into a common framework. The national ecological–economic system of Taiwan is used to illustrate the concept of emergy synthesis and the subsequent policy implications. The data of 1960, 1970, 1980 and 1987 were used for the analysis in order to examine the consequential evolving pattern of the rapid economic development during the past decades. In addition, the calculated emergy indices were also compared with several countries to understand further Taiwan's international status in terms of its ecological–economic system.

Keywords: emergy analysis, ecological-economics, environmental valuation, Taiwan, public policy.

1. Introduction

The complexity and scale of the interactions between human development and the natural environment have increased during the past decades. Urban and economic systems cannot be fully understood in isolation from their resource base—the ecological system within which they exist. Their ecosytem can provide people with services such as supply of energy, food, and water, maintenance of the gaseous quality of the atmosphere, recycling of nutrients essential to agriculture and forestry, etc., which are not only indispensable but also irreplaceable in terms of the functions they can serve in a human

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economy. Given our present large uncertainty about the true environmental state, and the limited availability of all forms of energy sources, prudent policy regarding the long-term ecological–economic interface must be developed and implemented to ensure maintenance of society's life supporting systems and enhancement of quality-of-life.

Over the past decades, much activity in academic institutions has been directed towards the development of methods and techniques for incorporating environmental values into planning and decision making processes. The major effort for these valuation techniques has been focused upon measuring the impact of development and the benefit of preserving the environment. For example, a number of EIA methods (Canter, 1977; Munn, 1979; Shopley and Fuggle, 1984) have attempted to develop an integrated approach to various tasks, such as identification, measurement, prediction, etc., involved in the completion of an environmental impact assessment. Because monetary units have a familiar meaning to decision-makers and the public, economic approaches such as cost-benefit analysis have also been applied to incorporate monetary units for the evaluation of resource transactions (McAllister, 1980). However, monetary units are difficult or impossible to apply to resources that are not typically marketed, for example, sunlight, wind, bacteria etc. (Westman, 1985). Ecologists and energy analysts observe that the human economy is not exempt from the laws governing natural systems. But there has been little or no sophisticated treatment of the physical attributes of the resource base in much of modern economic theory. Daly (1984) further pointed out that even if the imputed price of an environmental service is positive, the source of value is still seen as subjective to individual *wants*, rather than as the objective *needs* of humans or other species considered as biological entities bound together in ecological communities and social systems.

What is the true worth of the natural environment? How shall we go about evaluating environmental services? And, how could we incorporate the intrinsic value of the natural systems into the decision-making process? Given the highly complex properties of the natural environment, a more systematic method which includes environmental and economic interactions, on the basis of biophysical value theory, for collecting and incorporating the information about the functioning of the environment may be necessary to shadow price resources. This paper is an attempt to integrate, to some degree, the interdependencies between human economy and natural systems, using energy as the common denominator for measuring activity in both types of system. The island of Taiwan, Republic of China, is used as a case study to demonstrate this effort. Our basic approach is to provide an overview of what we perceive to be the essential properties of society's basic resource systems, including an assessment of the biophysical based macro-economic value of the natural environment. In order to compare the worth of different inputs from natural system and products of the human economy on any scale, it is necessary to use some common measure. The terms "transformity" and "emergy", initiated by Odum (1988), will be introduced in this paper as the principal conceptual tool of energy analysis for expressing the phenomena of hierarchy, energetic flows, and resource quality, and for linking together the systems of natural environment and human economy.

The primary aims of using the concept of emergy synthesis to illustrate the national ecological–economic system of Taiwan are as follows:

1. To demonstrate the applicability of a methodology, based on a broad concept of energy and general systems, for the study of regional systems in a quantifiable way.

2. To conduct a quantitative study of the energy and economic flows in Taiwan, including energy sources from the natural systems, and imported and exported goods and services from the human economy system.
3. To examine the evolving pattern of the ecological–economic system of Taiwan and its international status as compared to other countries.
4. To discuss the worth of an economic miracle in terms of quality-of-life in a rapidly developing country.
5. To indicate or show how the emergy synthesis could offer a more quantitative approach for public policy regarding the ecological–economic interface.

2. Emergy concept for environmental valuation

Ecology and economics share the same Greek roots, "Oikos", meaning "pertaining to the household" of nature and mankind respectively. Both disciplines address complex systems, but their conceptual and professional isolation have led to environmental and ecological policies which are mutually destructive rather than reinforcing in the long-term. It is well recognized that the economic activities of production and consumption are not independent of the global ecosystem (Ehrlich and Ehrlich, 1972; Odum, 1983; Martinez-Alier, 1987). Quantitative valuation of the natural environment is a prerequisite to the initiations of management decisions and to project evaluations concerning interactions between man and nature. But, with growth in scale of the human economy, the interface and non-market interdependencies with the ecosystem become more significant. The increasing externalities as a result of excessive scale has caused the inability of the market to solve the allocation problems (Daly, 1984).

The natural environment has frequently been seen as a common property resource, no accounting of real cost was made and no dollar payment was required for the uses of resources (Costanza, 1984). Environmental resources are generally valued at cost of extraction; the effects of economic production on natural environments are likewise valued at the cost of dumping or disposal. Christensen (1989) further pointed out that the calculation of social costs is ordinarily made in terms of current market prices which themselves do not reflect the full cost of the use of resources or environmental systems. Money paid for resource inputs goes to the human extractors in large part for the work in obtaining those resources and not for the work of the environmental systems that produce them.

Currently practiced environmental and resource economics basically cover the application of neoclassical economics to problems such as environmental pollution and resource depletion. A consensus has been reached by economists that perfect markets do not exist for natural environments because: (1) not all resources are privately owned; (2) owners of resources do not necessarily capture benefits from the use of their resources; and (3) no single owner can own all of any one resource (Costanza, 1984). According to neoclassical theory, judgements about the economic value of various goods and services are determined by the subjective tastes and preferences of individual consumers. There has been little or no sophisticated treatment of the physical attributes of the resource base in much of modern economic theory (Hall *et al.*, 1986). "Economic surrogates" such as travel cost, hedonic price, hypothetical valuation, etc., have frequently been applied by neoclassical oriented environmental economists to evaluate shadow prices for non-market resources (Westman, 1985). The inadequacy of these "willingness-to-pay" based approaches has been raised by Costanza (1984), Daly (1984), Ehrlich (1989), etc. for the following reasons. First, the measured value of a resource is based on the subjective individual preferences weighted by the present distribution of income and wealth. Second, the information for the true value of resources is seldom thoroughly and properly provided. Third, narrow physical boundaries are defined that result in the assumption of an infinite number of resources, and that a satisfactory substitute can always be found for the role of any one of them.

Energy analysts and ecologists argue that neither prices nor costs, determined within the economic subsystems, should be used to evaluate the worth of flows to and from the ecosystems. Modern economic theories have neglected the implications of the basic physical principles governing material and energy use for an economic theory of production, for the operation of a production-based price system, for macro-economic dynamics, and for longer-run growth processes and prospects (Christensen, 1989). There is nothing in the neoclassical theory to suggest any intrinsic or internal requirements of the human ecological system that should shape the process of resource valuation and use. The intrinsic value of goods and services has been confused greatly with market prices. Welfare is sometimes determined by total utility (use value). Prices measure marginal utility (exchange value), which cannot reflect reproduction values for critical environmental resources and services. A biophysical based method is needed to: (1) understand the roles that various natural and environmental resources play in sustaining or expanding economic activity; (2) examine the functioning of energy, water, land and labour in our economy; and (3) determine the real environmental impact and the consequent economic costs of development.

Ecological economics, a newly established discipline (see Costanza, 1989), aims to encourage new ways of thinking about the linkages between ecological and economics systems in a broader sense. Juan Martinez-Alier (1987) has also written the history and current status of ecological economics. Many early economists, including the physiocrats of the 18th century, focused their analysis on how human society interacted with, and was influenced by, natural systems and the attributes of the physical resources found in those systems. The classical approach started from a theory of production: the extraction of materials and food followed by the processing of materials. This material-processing approach can be considered as a proto-energetic approach to production which includes application of the principle of mass conservation to manufacturing production (Christensen, 1989). The treatment of natural resources and the physical assumptions of production theory reveal an early attention to the physical side of economic activity in classical economics which is absent in modern theories. Christensen (1989) calls for a reconstruction of the biophysical foundations of economic activity. A biophysical perspective can extend the classical approach to include the low-entropy energy and materials extracted from environmental systems and eventually returned as waste and the extracted high-entropy sources such as geothermal heat. Production and exchange in economic systems can therefore become part of a larger totality of interdependent material, energy and information exchanges.

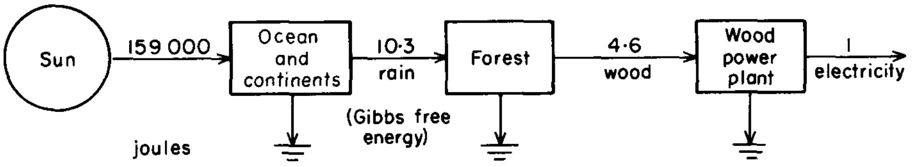
The physically based energy analysis, favoured by some ecologists to provide a monetary value for natural resources, can provide a more comprehensive framework for analysing economic and ecological systems that allows non-market information to be incorporated more easily. However, this is the part of gross economic product contributed by a resource. It is not to be considered the price someone should pay. Payments are only made to people, not to any environmental service. Energy is transformed successively between components of a system. For example, sunlight is transformed to plant organic matter, to herbivore, to carnivore, etc. The diagramming of energy storages and flows for use both in economic and ecosystem analysis has initially been suggested by Odum (1971) and continues to be a mainstream for the analysis of the man–nature interface (Odum and Odum, 1981; Odum, 1983; Odum, 1988). On the basis of general systems principles and the laws of thermodynamics, Odum has formulated a unifying theory of systems ecology including socio-economic aspects which has generated research activities that can be expected to change society's valuation of living natural systems.

In an attempt to define a biophysical value theory that is applicable with equal facility to ecological and economic systems, Odum noted that the reason why the past efforts in adopting energy analysis for studying the ecological–economic interface were not successful is due to the fact that all forms of energy (e.g. sunlight, water, fuel, etc.) do not accomplish an equivalent amount of work. In other words, lower quality energy (e.g. sunlight) is transformed to a higher quality energy (e.g. human services) in less quantity because energy is degraded during the transformation process—the 2nd law of thermodynamics. In order to take into account the different qualities of energy inherent in the hierarchy of systems components, two terminologies—"transformity" (previously called energy transformation ratio) and "emergy" (previously known as embodied energy)—were initiated by H. T. Odum, and can be defined as follows (Odum, 1988):

Transformity: the ratio of energy of one type required to produce a unit of energy of another type.

Emergy: the energy of one type required in transformations to generate a flow or a storage.

Figure 1 is an example showing a chain of energy transformation and the solar transformities for the products of each progressive transformation. With the concept of transformity, we have a scale of energy quality that indicates the position in the energy hierarchy. The higher the quality of energy, the higher the transformity. Calculations of



Solar transformities in solar emjoules per joule (sej/J):

Rain: $\frac{159\ 000 \text{ solar joules}}{10{\cdot}3 \text{ rain joules}} = 1{\cdot}54 \times 10^4$ sej/J

Wood: $\frac{159\ 000 \text{ solar joules}}{4{\cdot}6 \text{ wood joules}} = 3{\cdot}46 \times 10^4$ sej/J

Electricity: $\frac{159\ 000 \text{ solar joules}}{1 \text{ electricity joule}} = 15{\cdot}9 \times 10^4$ sej/J

Figure 1. Example of chain of energy transformation. Source: Odum *et al.* (1987).

solar transformities for various items of resources (e.g. wind, rain, river, soil, biomass, fuel, etc.) have been performed by H. T. Odum and his colleagues at The University of Florida, for example, see Odum and Odum (1983), Odum *et al.* (1987).

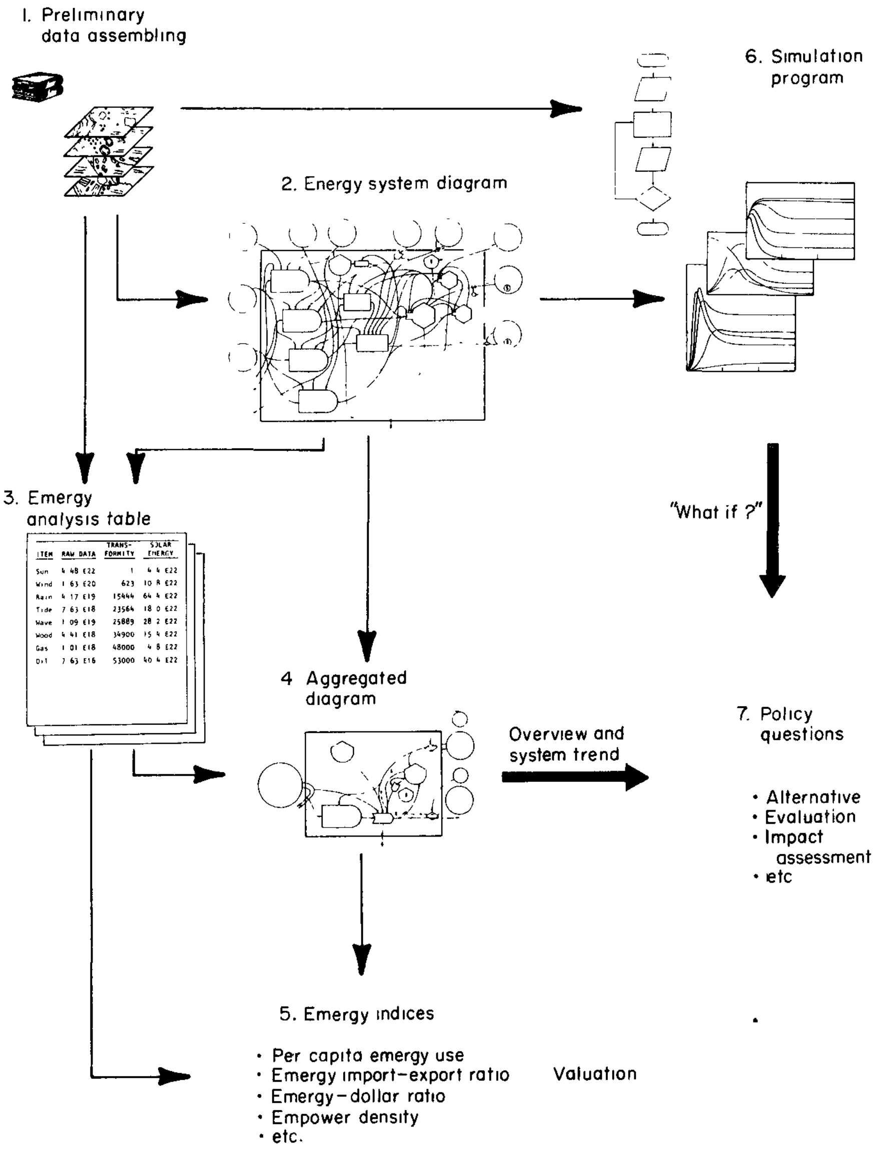
Solar emergy of a flow or storage is the solar equivalent energy required to generate that flow or storage. Its units are solar emjoules (sej). After the energy content (e.g. joule) of a flow has been estimated, it can be multiplied by its solar transformity to obtain its solar emergy. In this way, various flows and storages of the ecological–economic system can be readily evaluated on a comparable energy basis for what has been contributed to a system. Energy is not an adequate measure of value, because the highest valued processes such as human service and information flow have very tiny energies. Emergy can be used to represent both the quality and the quantity of energy that any input or product of the economy represents. Furthermore, the emergy concept offers an alternative and complementary viewpoint of value on the biophysical nature of human activity.

3. Methodology

For an ecosystem, there are storages of biomass or energy at each trophic level, with various inflows and outflows of imports, feeding, maintenance, exports etc. For the economic system, there can be storages of money, labour, land, etc., and flows of energy, goods and services etc. This paper uses the energy language symbols of Odum (1971, 1983) for representing the storages and flows of the human ecological system of Taiwan. In order to thread together the human economy and natural systems, energy was used as a common denominator. Further, the actual energy values presented in this paper are converted to solar equivalent emergy units. All flows of energy can be compared by expressing them in quantity of energy of one type. And most importantly, non-market-priced natural resources can also be valuated.

The study procedure for the emergy analysis of Taiwan is presented in Figure 2 as the following stages:

1. Preliminary data assembling: collect data from various sources of geographical or economic information and statistics of the study area.
2. Energy systems diagram: draw a sufficiently detailed inventory diagram, using symbols of the energy circuit language developed by Odum (1971, 1983), to gain an initial network overview and organize data-gathering efforts.
3. Emergy analysis table:
    - 3.1. List items of main flows from indigenous sources, imported sources, exports, and storages.
    - 3.2. Derive raw data for listed items. Data on energy inputs are usually expressed in energy units (joules), mineral in mass units (grams), and human services in currency units (i.e. $).
    - 3.3. Evaluate listed flows and storage reserve in emergy units (product of raw data and transformity) and macro-economic dollars (obtained by dividing the emergy units by the national emergy–dollar ratio) to facilitate comparisons and public policy inferences.
4. Aggregated diagram: with the help of the energy systems diagram (step 2), group important components into a simplified emergy diagram. Main categories of emergy are also aggregated into those believed to be important to system trends, and those of particular interest to current public policy questions.



ITEM	RAW DATA	TRANS-FORMITY	SOLAR EMERGY
Sun	4 48 E22	1	4 4 E22
Wind	1 63 E20	623	10 8 E22
Rain	4 17 E19	15444	64 4 E22
Tide	7 63 E18	23564	18 0 E22
Wave	1 09 E19	25889	28 2 E22
Wood	4 41 E18	34900	15 4 E22
Gas	1 01 E18	48000	4 8 E22
Oil	7 63 E16	53000	40 4 E22

Figure 2. Procedure of emergy synthesis for public policy.

5. Emergy indices: from the aggregated categories of emergy, various indices such as per capita emergy use, fraction of indigenous emergy used, emergy import–export ratio, etc., can be calculated to illustrate the ecological–economic interface.
6. Simulation program: a computer simulation program can also be written to study the dynamic behaviours of a macroscopic minimodel. Rather than used for prediction, the program can be used for "what if" experiments answering policy questions.
7. Public policy questions: evaluations, emergy indices, and simulations can be used to consider current public policy issues, and initiate alternatives for generating more realistic contributions to the unified economy of man and nature.

The procedure summarized above will be described, in whole or in part, in the following sections of this paper. This open system energy approach offers an alternative and complementary viewpoint on the biophysical nature of human activity. The relationship between energy and economic activity within the human ecological system can be quantified to assess the work that natural systems perform and to evaluate negative environmental externality in a comparable way. Calculation of the indirect costs of producing goods and services is facilitated by the ratio of total emergy use to GNP. Macro-economic dollar values of each energy flows and storages can be derived by dividing its emergy value by the emergy–dollar ratio. The environmental services provided by sunlight, rain, wind, etc. can thus be evaluated in dollars of gross national product. However, the macro-economic value is not to be confused with, or substituted for, regular economic values which are micro-economic market prices based on individuals' willingness-to-pay.

Odum and his colleagues at The University of Florida have applied emergy analysis to a number of countries for the evaluation of the total emergy uses of each country and their ecological–economic status. Further details of emergy synthesis can be found in Odum (1983), Odum and Odum (1983), and Odum *et al.* (1987).

4. Overview of the ecological–economic system of Taiwan

Taiwan is a rather elongated mountainous island, measuring some 370 km in length and 130 km at its point of greatest width, which lies off the south-east coast of the Chinese mainland, separated by the Taiwan Strait that is about 145 km wide at its narrowest point (see Figure 3). The natural forested beauty of the island lead Portuguese sailors in 1590 to name it "Ilha Formosa", meaning beautiful Island. The island has a subtropical climate with hot, rainy summers and mild winters. Average temperatures are about 15°C (59°F) in the winter and 26°C (79°F) in the summer. The average annual rainfall is 2565 mm. Typhoons occur almost every year, especially in the summer. Aborigines were the first inhabitants of Taiwan. Some Chinese came to the Island from the mainland as early as the 500s, but large settlements did not begin until the 1600s. Dutch traders occupied a Taiwanese port from 1624 until 1661, driven out by Koxinga, an official of the Chinese Ming dynasty. China ceded Taiwan to Japan in 1895 as a result of the first Chinese–Japanese War. The island remained under Japanese control until 1945, when World War II ended, and has been a province of the Republic of China ever since.

The island is densely populated, with about 20 million people living on 36 000 km^2 of land (550 people km^{-2}). Moreover, the majority of the people live on the coastal plain that makes up the western third of the island. The central portion of the island is dominated by forested mountains, which cover about half of Taiwan. The highest peak rises 3997 m above sea level and the mountains drop sharply to the Pacific Ocean along the eastern coast. The major cities are situated along the western coast. Taipei, on the northern end of the island, is the capital and the largest city of Taiwan, it has approximately 5 million people in its metropolitan region, and also is the seat of the Chinese Nationalist Government. Kaohsiung is the second largest city in Taiwan, and is situated on the southern portion of the western coast. An expressway connects major cities on the western coastal plain.

Taiwan has few natural resources except its mountain forests. Mineral resources include coal, marble, gold, petroleum and natural gas. Energy supplies have always been a problem, and Taiwan is heavily dependent on imported petroleum. There are three nuclear power plants in operation, providing in 1985 around 52% of Taiwan's total

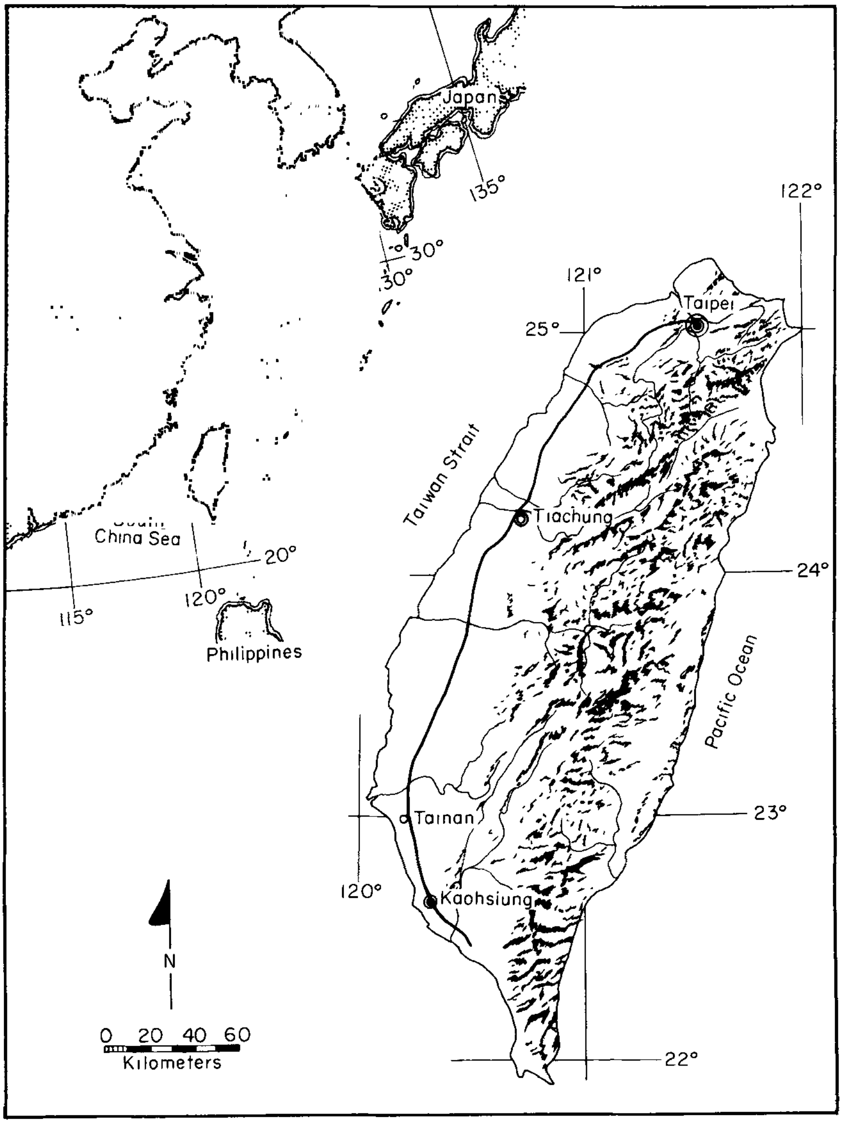


Figure 3. Geographic overview map of Taiwan.

power generation. Despite the lack of natural resources, Taiwan's economy has developed rapidly since 1950, owing mainly to the considerable expansion of foreign trade. Agriculture's role in the economy has declined significantly since the 1950s; in 1952, it provided more than 90% of total exports and contributed 56·1% of Taiwan's GDP, while employing 56% of the labour force. The principal crops were rice, sugar cane and sweet potatoes. By 1983 however, agricultural products and processed food provided less than 7% of total exports; in 1986, the sector contributed only 5·6% of GDP, and employed 16·6% of the labour force. By the 1980s, Taiwan was among the world's 20 leading exporting countries. The petrochemical industry in Taiwan is the third largest in Asia. Between 1970 and 1980, Taiwan's gross domestic product (GDP) expanded, in real terms, at an average rate of 9·5% per year. The current per capita gross national product (GNP) is approximately 6000 U.S. dollars. However, as the island's industrial infrastructure developed, the economy progressed towards less self-sufficiency, from the ecological–economic system's point of view, due to its lack of indigenous resources.

During the 1970s, a number of nations ended their diplomatic relations with Taiwan and established ties with communist China. However, trade and economic links with the rest of the world have thrived. Exports are still dominated by the U.S. market, which accounts for more than one-third of Taiwan's foreign trade, followed by Japan and Hong Kong. As a result of continued trade surpluses, Taiwan's reserves of foreign exchange increased from U.S.$2205 m. at the end of 1980 to U.S.$73 500 m. by November 1987, leading to pressure from abroad to revalue the New Taiwan dollar. In addition to this pressure, the people in Taiwan, especially the environmental groups, have raised the awareness of environmental degradation due to the rapid economic development, and called for the preservation of the natural environment and the enhancement of the quality-of-life.

Figure 4 is a systems diagram of the main components of the economy of man and nature in Taiwan. Circular symbols outside the frame are causal influences from outside sources, and the main sectors and productive interactions are shown within the frame that represents the Taiwan boundary. Areas of coastal ecosystems, inland wilderness and agricultural system are shown by productive subsystems on the left. The electric utility relies on imported fuels and indigenous mineral resources and hydropower to generate power for industrial and city systems. The money gained from exporting manufactured commodities contributes a major portion of the GNP, which is also used to purchase fuel, raw materials and goods and services to generate economic activities.

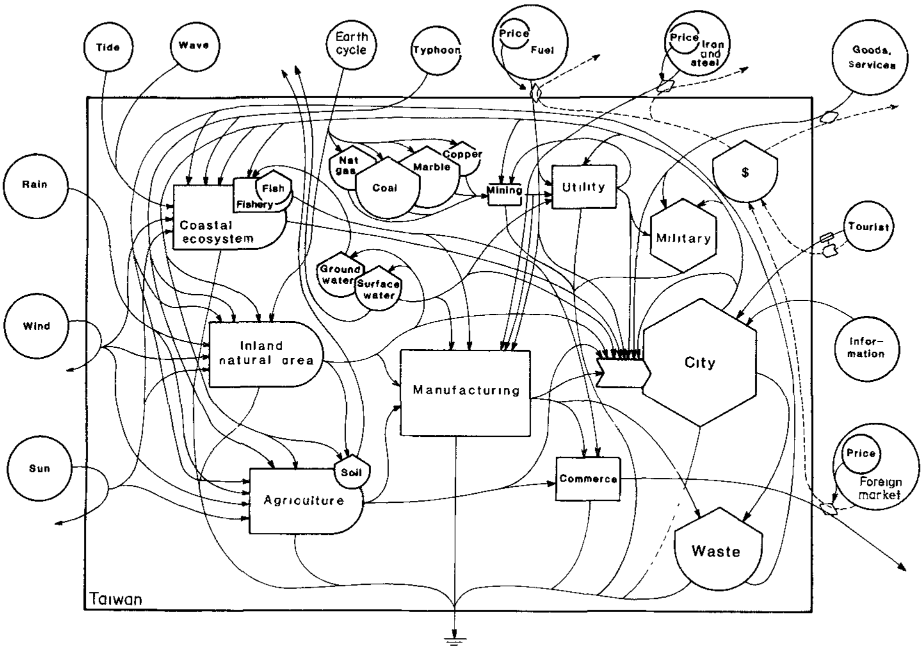


Figure 4. Energy system diagram of Taiwan.

5. Emergy synthesis overview of Taiwan

5.1. EMERGY ANALYSIS TABLE AND EMERGY INDICES

Based on the preliminary understanding of the ecological–economic system of Taiwan (Figure 4), a category of items of energy flows such as renewable, imported, and non-renewable indigenous sources, exports, etc. were listed for the study of Taiwan's status in terms of its ecological–economic interface and the consequence of rapid economic development. The data of 1960, 1970, 1980 and 1987 were used for the analysis in order to have a perspective of the evolving pattern of the emergy uses of Taiwan.

As shown in Table 1, each item of the annual flows that are important for studying the ecological–economic interface of Taiwan was evaluated, using data for 1987, in raw units (e.g. energy, mass, or $) which are typical for that class of input. The solar emergies of each of the flows were obtained from the product of raw data and solar transformities. Macro-economic values of each of the flows were then calculated in units of U.S.$ for that particular year. Comparison of emergy and macro-economic values among listed items can reveal the relative contribution of each input and output to the national economy in Taiwan. Due to the limited availability of natural resources, the emergy flows from renewable sources and local non-renewable sources to the national economy are relatively small. However, the ability to attract outside high emergy in fuels, goods and services (medium- and high-transformity inputs) depends on being able to match these inputs with environmental interactions. Maintaining services by environmental systems helps to maximize the economy based on imported emergy.

Evaluation of principal emergy flows can provide quantitative measures of the ecological–economic system of the studied area. Based on the examination of the aggregated emergy flows for Taiwan (see Table 2 and Figure 5), it becomes apparent that imported fuel and goods and services are the principal sources for the national economy in Taiwan. Specifically, Taiwan operated its economy on 4% renewable resources, 24% local non-renewable resources, 30% imported fuels, and 42% imported goods and services. In this paper, the emergy–dollar ratios of imports for each year were calculated by dividing the world emergy flux (combined biosphere crustal system plus world fuel use) by the world economic product (Figure 6). Because Taiwan is lacking in natural resources and its economy relies mainly on exporting manufactured commodities, there is no direct export of non-renewable resources. As shown by Figure 5(b), both emergy flows of imported fuels and goods and services and exported finished products are the major driving forces of economic growth, but they are also responsible for the consequent waste that is generated.

Tables 3–6 summarize the results by comparing several important emergy indices of Taiwan (1980) with 13 other countries previously analysed by Odum and Odum (1983) for the purpose of revealing the international status of the ecological–economic system of Taiwan. The concentration of emergy use is compared in Table 3. High population density and low empower density signify poor countries, for example, India. Taiwan, an urbanized and developed country, has the highest population density among these 14 countries, and a rather high concentration of emergy use indicates that Taiwan is moving toward the centre of the world economic hierarchy. Because the index of per capita emergy use includes the substantial life support system of rural areas, it is a better general index of standard of living than income. Taiwan has a relatively high empower density, but because of its high population, the index of emergy use per person is relatively low, indicating its lower quality-of-life as compared to other developed countries (see Table 4).

TABLE 1. Emergy analysis table of resource and economic flows of Taiwan in 1987

Note	Item	Raw data	Transformity (sej/unit)	Solar emergy ($\times 10^{20}$ sej)	Macroeconomic value ($\times 10^{6}$ 1986 U.S.$)
Renewable sources					
1.	Sunlight (J)	$2{\cdot}11 \times 10^{20}$	1	2·11	112·57
2.	Wind, kinetic (J)	$5{\cdot}34 \times 10^{15}$	623	0·03	1·78
3.	Rain, geopotential (J)	$6{\cdot}64 \times 10^{17}$	8888	59·03	3149·66
4.	Rain, chemical (J)	$4{\cdot}46 \times 10^{17}$	15444	68·94	3678·40
5.	Tide (J)	$2{\cdot}72 \times 10^{17}$	23564	0·64	34·25
6.	Waves (J)	$1{\cdot}62 \times 10^{16}$	25889	4·20	224·36
7.	Earth cycle (J)	$1{\cdot}08 \times 10^{17}$	29000	31·32	1671·16
8.	Wood consumption (J)	$6{\cdot}26 \times 10^{15}$	34900	2·19	116·61
9.	Typhoon (J)	$1{\cdot}32 \times 10^{17}$	41000	53·94	2878·04
10.	Hydro-electricity (J)	$2{\cdot}56 \times 10^{16}$	159000	40·68	2170·39
11.	Water consumption (J)	$2{\cdot}18 \times 10^{16}$	665714	144·95	7734·45
Imports and outside sources					
12.	Crude petroleum (J)	$8{\cdot}84 \times 10^{17}$	53000	468·52	24998·98
13.	Petroleum product (J)	$5{\cdot}54 \times 10^{16}$	66000	36·54	1949·55
14.	Iron ore (g)	$7{\cdot}14 \times 10^{12}$	$8{\cdot}55 \times 10^{8}$	61·01	3255·10
15.	Iron and steel P. (t)	$8{\cdot}80 \times 10^{5}$	1.78×10^{15}	15·66	835·35
16.	Logs (J)	$9{\cdot}91 \times 10^{14}$	34900·00	0·35	18·45

17. Goods ($)	$1·22 \times 10^{10}$	$2·00 \times 10^{12}$	243·04	12968·03
18. Services ($)	$7·20 \times 10^{9}$	$2·00 \times 10^{12}$	144·00	7683·50
19. Tourists ($)	$6·16 \times 10^{8}$	$2·00 \times 10^{12}$	12·33	657·72
Non-renewable sources from within Taiwan				
20. Natural gas (J)	$4·02 \times 10^{16}$	48000	19·28	1028·54
21. Coal production (J)	$4·39 \times 10^{16}$	39800	17·48	932·93
22. Electricity use (J)	$2·36 \times 10^{17}$	159000	375·63	20042·79
23. Marble production (g)	1.10×10^{13}	55000000	6·05	322·81
24. Copper (g)	$5·00 \times 10^{10}$	$6·77 \times 10^{10}$	33·85	1806·16
25. Earth loss (T)	$8·64 \times 10^{6}$	$1·71 \times 10^{15}$	147·74	7883·27
26. Net top soil loss (J)	$9·86 \times 10^{14}$	62500	0·62	32·88
27. Nuclear elec. use (J)	$1·15 \times 10^{17}$	159000	182·32	9728·22
Exports				
28. Goods and services ($)	$6·05 \times 10^{10}$	$1·87 \times 10^{12}$	1134·57	60500·00
Dollar flows				
29. GNP ($)	$9·93 \times 10^{10}$	$1·87 \times 10^{12}$	1860·62	99300·00
30. $ from abroad ($)	$3·00 \times 10^{8}$	$1·87 \times 10^{12}$	5·62	300·00
31. $ paid abroad ($)	$7·33 \times 10^{8}$	$1·87 \times 10^{12}$	13·74	733·00
Waste produced				
32. Waste water (J)	$1·31 \times 10^{16}$	665714	86·97	4640·00
33. Solid waste (J)	$2·23 \times 10^{16}$	1800000	402·05	21500·00

TABLE 2. Aggregated emergy flows for Taiwan in 1987

Letter	Item	Solar emergy (× 10^{20} sej/year)	Dollar (× 10^{9} $)
R	Renewable sources used	69·58	
N	Non-renewable sources flow within Taiwan	445·83	
	N0 Dispersed rural source	146·17	
	N1 Concentrated use	299·66	
	N2 Exported without use	0·00	
F	Imported fuels and minerals	566·06	3·00
G	Imported goods	16·00	1·00
I	Dollar paid for imports		42·16
P2I	Emergy value of goods and services imports	843·14	
I3	Dollar paid for imports minus goods		38·16
P2I3	Imported services	763·14	
E	Dollar paid for exports		60·54
P1E	Emergy value of goods and services exports	1134·57	
B	Exported products transformed w/n Taiwan	1003·38	
E3	Dollars paid for exports minus goods		7·00
P1E3	Exported services	131·19	
W	Emergy value of waste	489·02	
X	Gross national product		9·93
P2	World emergy/$ ratio, used for imports	2·00 × 10^{12} sej/$	
P1	Taiwan emergy/$ ratio, used for Taiwan and exports	1·87 × 10^{12} sej/$	

5.2. EMERGY AND ECONOMIC EFFICIENCY

Emergy–dollar ratio (total emergy used divided by GNP) can be seen as measures of the real buying power of currency and the ability of labour to compete in attractive labour-intensive economic activity. Higher values of emergy–dollar ratio are found in rural and less developed countries where more energy for supporting human economy comes

TABLE 3. Concentration of emergy use of 14 countries in 1980

Nation	Area m^2(× 10^{10})	Population density people km^{-2}	Empower density sej/m^2/year (× 10^{11})
Netherlands	3·70	378	100
West Germany	24·90	247	70·4
Taiwan	3·60	494	37·2
Switzerland	4·10	154	17·7
Poland	31·20	111	10·6
Dominica	0·08	107	8·8
U.S.A.	940·00	24·2	7·0
Liberia	11·10	16·1	4·18
Spain	50·50	68·5	3·12
New Zealand	26·90	11·5	2·94
Brazil	918·00	13·2	2·08
India	329·00	192	2·05
Soviet Union	2240·00	11·6	1·71
Australia	768·00	1·9	1·42

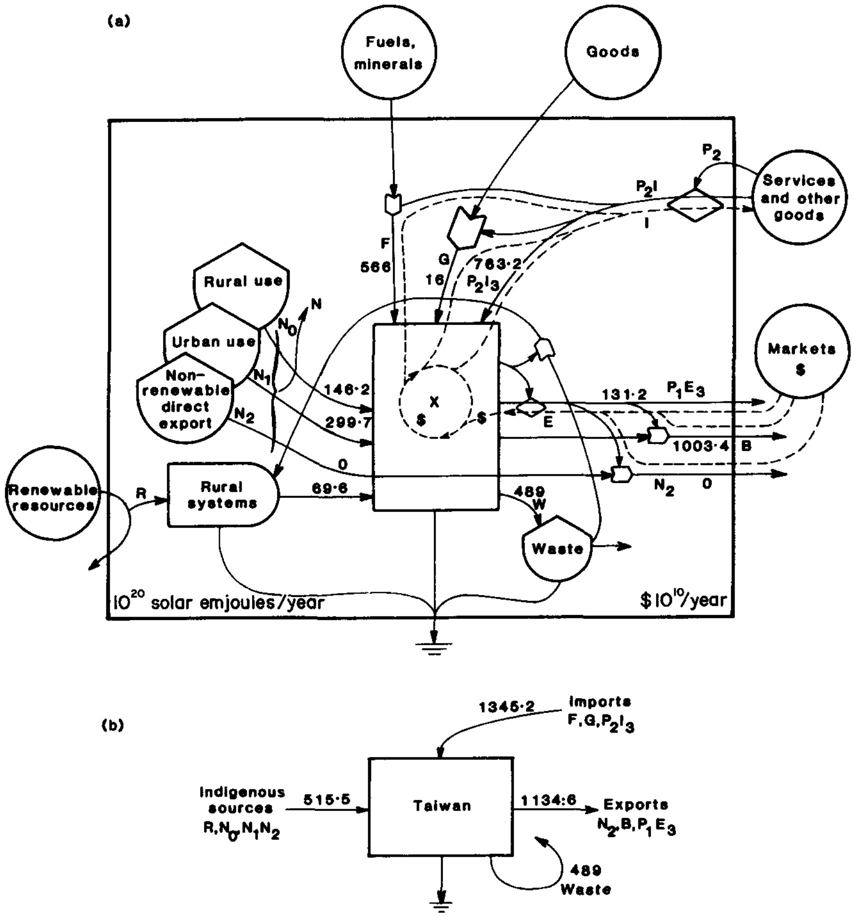


Figure 5. Aggregated diagram of emergy flows for Taiwan in 1987.

TABLE 4. Emergy use and population of 14 countries in 1980

Nation	Emergy used sej/year ($\times 10^{20}$)	Population ($\times 10^6$)	Emergy use per person sej/person/year ($\times 10^{15}$)
Australia	8850	15	59
U.S.A.	66400	227	29
West Germany	17500	62	28
Netherlands	3702	14	26
New Zealand	791	3·1	26
Liberia	465	1·3	26
Soviet Union	43150	260	16
Brazil	17820	121	15
Dominica	7	0·08	13
Switzerland	733	6·37	12
Poland	3305	34·5	10
Taiwan	1340	17·8	8
Spain	2090	134	6
India	6750	630	1

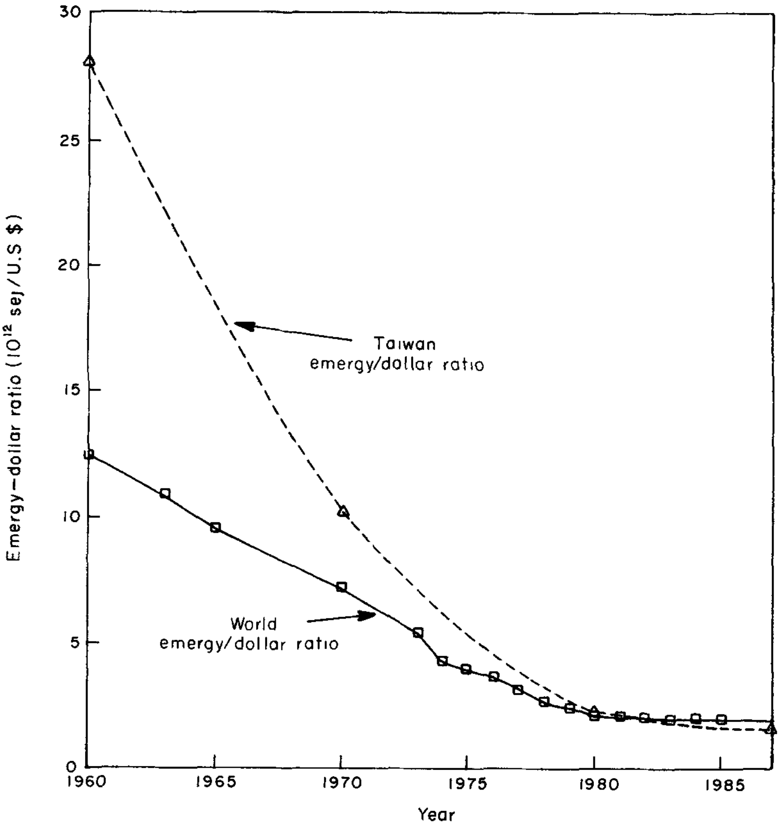


Figure 6. Emergy–dollar ratio in Taiwan.

Table 5. National activity and emergy–dollar ratio of 14 countries in 1980

Nation	Emergy used sej/year (× 10^{20})	GNP $/year (× 10^{9})	Emergy/$ (× 10^{12})
Liberia	465	1·34	34·5
Dominica	7	0·075	14·9
Brazil	17820	214	8·4
India	6750	106	6·4
Australia	8850	139	6·4
Poland	3305	54·9	6
World	188000	5000	3·8
Soviet Union	43150	1300	3·4
New Zealand	791	26	3
U.S.A	1340	58·3	2·3
West Germany	66400	2600	2·6
Taiwan	17500	715	2·5
Netherlands	3702	16·6	2·2
Spain	2090	139	1·6
Switzerland	733	102	0·7

directly from the natural environment without payments of money. The gross national product in Taiwan is driven mainly by the imported emergy of fuel and goods and services, so that the emergy–dollar ratio in 1980 was relatively low (see Table 5), representing its highly industrialized state. Status in international exchange of Taiwan is given in Table 6. Similar to other small developed countries such as The Netherlands and Switzerland, Taiwan has low self-sufficiency in emergy use; most of the emergy used were imported from other countries. However, as shown by the exchange ratio in Table 6, Taiwan is also taking advantage of emergy exchange.

During the past decades, Taiwan has achieved an economic miracle resulting from international trade, which can also be shown by the rapid increase in emergy used. For the purpose of revealing the changing pattern of the ecological–economic interface in Taiwan, statistical data of 1960, 1970, 1980 and 1987 were used. Table 7 summarizes the results of emergy indices of Taiwan of these 4 years. Total emergy used (item 5) has increased more than four times since 1960, an increase derived mainly from imported sources (item 3) for the purpose of exporting manufactured goods (item 6). The fraction of emergy used derived from home sources (item 7) has dropped from 0·64 to 0·28, and the fraction of emergy used that is free (local natural resources) dropped from 0·49 to 0·12. Based on the emergy indices of imports vs. exports (items 8 and 9), Taiwan's status in ecological–economic system changed from rural country to industrialized developed country during the period of 1960–1970. Advantages received in trade can be found from the fact that imported emergy exceeded exported emergy in the 1960s.

5.3. EMERGY AND ECONOMIC GROWTH

As a consequence of the dramatic increase in total emergy used, the empower density also increased significantly. Emergy use per person also increased, but the rate of change is not as fast as empower density due to the rapid population growth. The population growth in Taiwan was driven mainly in the past by the economic necessity for larger families in a labour-intensive society. However, the consequence is human ecological

TABLE 6. Emergy self-sufficiency ratio and exchange ratio of 14 countries

Nation	Emergy from within (%)	Emergy received / Emergy exported
Netherlands	23	4·3
West Germany	10	4·2
Switzerland	19	3·2
Spain	24	2·3
U.S.A.	77	2·2
Taiwan	24	1·89
India	88	1·45
Brazil	91	0·98
Dominica	69	0·84
New Zealand	60	0·76
Poland	66	0·65
Australia	92	0·39
Soviet Union	97	0·23
Liberia	92	0·151

TABLE 7. Emergy indices overview of the evolving ecological–economic system of Taiwan

Item	Name of index	Expression	Quantity			
			1960	1970	1980	1987
1	Renewable emergy flow ($\times 10^{20}$ sej/year)	R	69·58	69·58	69·58	69·58
2	Flow from indigeneous non-renewable reserves ($\times 10^{20}$ sej/year)	N	210·02	234·65	248·27	445·83
3	Flow of imported emergy ($\times 10^{20}$ sej/year)	F + G + P2I3	158·37	255·83	1022·11	1345·20
4	Total emergy inflow ($\times 10^{20}$ sej/year)	R + N + F + G + P2I3	437·96	560·06	1339·95	1860·62
5	Total emergy used ($\times 10^{20}$ sej/year)	U = N0 + N1 + R + F + G + P2I3	437·96	560·06	1339·95	1860·62
6	Total exported emergy ($\times 10^{20}$ sej/year)	B + P1E3	327·63	172·62	542·27	1134·57
7	Fraction of emergy used derived from home sources	(N0 + N1 + R)/U	0·64	0·54	0·24	0·28
8	Imports minus exports ($\times 10^{20}$ sej/year)	(F + G + P2I3) − (N2 + B + P1I3)	−169·26	83·21	479·84	210·63
9	Ratio of exports to imports	(N2 + B + P1I3)/(F + G + P2I3)	2·07	0·67	0·53	0·84
10	Fraction used, locally renewable	R/U	0·16	0·12	0·05	0·04
11	Fraction of use purchased	(F + G + P2I3)/U	0·36	0·46	0·76	0·72
12	Fraction of use that is free	(R + N0)/U	0·49	0·39	0·16	0·12
13	Use per unit area ($\times 10^{12}$ sej/m^2/year)	U/area	1·22	1·56	3·72	5·17
14	Use per person ($\times 10^{20}$ sej/person)	U/population	4·06	3·82	7·53	9·46
15	Ratio of use to GNP, emergy/dollar ratio (sej/$)	P1 = U/GNP	2.81×10^{13}	$1·03 \times 10^{13}$	$2·30 \times 10^{12}$	$1·87 \times 10^{12}$
16	Ratio of efficiency use to GNP, useful emergy/dollar ratio	P0 = (U − W)/GNP	$1·72 \times 10^{13}$	$5·29 \times 10^{12}$	$1·63 \times 10^{12}$	$1·38 \times 10^{12}$
17	Ratio of waste to renewable	W/R	2·45	3·90	5·57	7·03
18	Ratio of waste to use	W/U	0·39	0·48	0·29	0·26
19	Ratio of waste to GNP (sej/$)	W/GNP	$1·09 \times 10^{13}$	$4·97 \times 10^{12}$	$6·65 \times 10^{11}$	$4·93 \times 10^{11}$
20	Emergy investment ratio	(F + G + P2I3 + N0 + N1)/R	5·29	7·05	18·26	25·74

poverty which can be revealed from the low per capita emergy use (item 16; also see Table 4). The significant decline of the emergy–dollar ratio, from $28{\cdot}1 \times 10^{12}$ sej/\$ in 1960 to $1{\cdot}78 \times 10^{12}$ sej/\$ in 1987 (item 5; also see Figure 6), indicates change from an economy based on direct use of resources to an economic one where resources reach people through buying and selling with manufactured goods. The free subsidy from the environment which made lower wages possible has decreased. The emergy–dollar ratio is now the same as in the U.S. Therefore, the national economy of Taiwan can no longer rely on labour-intensive industry. Emergy investment ratio (item 20) is the ratio of the emergy fed back from the economy (including resources from within and imported) to the emergy from the free, local renewable resources (R), such as sun, wind and rain. Highly developed countries have higher investment ratios, usually greater than 7; in undeveloped areas, it could be much less than 1·0 (Odum and Odum, 1983). If the country receives more emergy from the urban economy using imported resources, the investment ratio will be high, and will result in increasing prices and an inability to compete in the world market. As shown by Table 7, the emergy investment ratio of Taiwan increased from 5·29 in 1960 to 25·74 in 1987. The reasons for this high emergy investment ratio in Taiwan are its limited renewable energy flow and the necessity of imported emergy of fuels and goods and services for maintaining its economic viability. The economy in Taiwan is moving toward the status of less self-sufficiency. The issue for such a high investment ratio is not just whether it is economical or not, but also a concern for environmental degradation. This measure can also be seen as an index of the environmental loading of economic activity. Given a finite supply of renewable natural resources, the capability to assimilate waste generated from production and consumption activity without causing adverse environmental effects is, from a macro perspective, fixed. This pressure of environmental degradation resulting from rapid economic development in Taiwan can also be detected from the ratio of waste to renewable emergy (item 17). Due to the fact that a great portion of the waste is left untreated, a ratio of efficiency use to GNP (item 16) is also calculated as a supplementary index to emergy–dollar ratio (item 15). Obviously, the real buying power should be smaller than the emergy–dollar ratio, because the emergy of untreated waste is not useful and is not presently being incorporated into the human economy; it is, so to speak, useless. A further benefit of increased emergy efficiency would be reduced levels of pollution associated with development and consumption activities for a given level of economic output. In addition, a subsidy must be made from the human economy to the natural environment in order to reinforce the services provided by the natural system and to maintain a balanced relationship between man and nature. Otherwise these systems will be drained.

6. Discussion and future research

The evaluation of the natural environment, especially the non-market-priced services, has always been a critical concern for both decision makers and academics. Different disciplines, such as ecology and economics, or even different schools or economics (classical and neoclassical), have different theoretical and methodological perspectives for evaluating the true worth of the natural system. This paper does not intend to provide easy solutions to problems between classical and neoclassical economic theories regarding interactions between human and natural systems. The emergy analysis of Taiwan is conducted to demonstrate an environmental basis for economic values by reducing all inputs and outputs of the economy to a common energy measurement—solar emergy.

The approach of emergy analysis to provide shadow prices for the natural environment is fundamentally based on a biophysical and scientific analysis for evaluating the worth of environmental services to the human economy. Using emergy indices, it is quite clear why the manufacturing and export of merchandise since the 1960s has caused prosperity and rapid economic growth in Taiwan. The ecological–economic status of Taiwan has been changed from that of a rural country to that of an industrialized country. Because of its limited availability of natural resources, Taiwan has to rely a great deal on imports and exports from and to other countries. However, the consequence of growth in economic activity is not without disadvantages—the increase of waste generated from production and consumption activity. The high density of population has resulted in difficulties of enhancing the living standard in Taiwan. Moreover, because of its industrialized status (high emergy–dollar ratio), Taiwan can no longer rely on labour-intensive manufacturing activity. The remedy, from the point of view of maintaining prosperity and enhancing quality-of-life in Taiwan, is to re-establish a net balance of emergy in foreign trade. This means that the national economy has to be restructured to shift from labour-intensive industry to high-technological based industry. Further, during the past decades, economic development has been the first priority of national policy, little effort was made to maintain the natural system. In order to balance the relationship between man and nature and to enhance the quality-of-life for the people in Taiwan, a return from the economy must be made to maintaining the life-support systems by, for example, rebuilding soils, waste treatment, or augmenting natural processes concentrating mineral storages.

The concept and approach presented in this paper can complement the neoclassical analysis of how human preferences influence the allocation of goods and services in an economy while providing a framework that links the natural environment to contemporary socio-economic models of human welfare. However, this approach should be viewed as a supplement to, rather than a replacement for, standard economic and environmental analyses. The macro-economic value, proposed in this approach, is useful for public policy considerations but should not be substituted for market prices for the transactions of the market place.

We envisage the continuing application of emergy synthesis for studying the ecological–economic interface of Taiwan and for answering policy questions in several directions:

1. How can economic development and environmental protection be made complementary? What is the best combination, in terms of the emergy indices introduced in this paper, for the ecological–economic status of Taiwan?
2. How can the emergy synthesis be applied to a metropolitan region, for example: Taipei, and its subsystems (e.g. water resources, solid waste management, etc.) for initiating sound management policies for growth?
3. If a certain amount of land area is required for waste management, what is the best distribution of land use?
4. If world fuel prices rise relative to other prices in the future, what economic pattern will maximize emergy in Taiwan?

Taiwan seems like a challenging example to begin the design of policy and to plan for the coupling of the systems of man and nature, and for insuring a competitive and long-term surviving system. Because Taiwan is shifting from a rural state to an economic hierarchical centre, it will be very useful to study the emergy exchanges between Taiwan and its major trading partners, such as the U.S., Japan, Germany and Hong Kong. If the total exchange between two countries could be based on emergy rather than money, equity could be arranged which might improve the international co-operation, enriching the world economy and fostering peaceful relationships.

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