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Urban ecosystems, energetic hierarchies, and ecological economics of Taipei metropolis

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Urban systems cannot be fully understood in isolation from the ecological system in which they exist. Past research projects which analysed energy in urban systems have focused on efficiency and conservation and the analysis of energetic flows that interconnect urban economic and ecological systems have not received much attention. The underlying theme of this paper is the application of ecological energetic analysis to bridge that gap. The energy evaluation of Taiwan, and the development of a global classification of ecological economic systems indicate that in less than half a century, Taiwan has changed from a rural country with an economy based on raw commodity production, to one that is highly industrialized with a lower self-sufficiency of emergy use. using a taxonomic approach, Taiwan can further be classified into four urban ecological economic systems: (1) agricultural settlement; (2) surburban industry; (3) urban metropolis; and (4) resource production. The distribution of these four systems also reveals the spatial energetic hierarchy within Taiwan. Finally, in concluding this paper, future directions for continuing research on urban energetic flows are suggested.

Keywords: urban ecosystems, energetic hierarchy, emergy synthesis, ecological economics, classification, Taiwan, Taipei metropolis.

Introduction

Cities act as centres of population, economic production and consumption, they are dynamic socio-economic entities and play a driving role in the development of regional, national and even international economies. Economists see cities as loci for intense socio-economic interaction among individuals and firms, and as engines of production and national economic growth. On the other hand, ecologists highlight the extended relationships among concentrated human populations, patterns of consumption, and the inward flows of energy and material. Nowadays, it has become evident that the urban economic system affects not only the environment, but is in some sense a heterotrophic system that has to depend on the surrounding natural environment for life-support services.

From an ecological economic perspective, the expansion of the urban area and its associated economic activities is limited by its dependence on the life-support systems, (Folke, 1991). Previous planning efforts for resource development have frequently extrapolated existing population growth and per capita resource consumption into the future as a basis for resource development planning, thus resulting in an imbalance between supply and demand in the metropolitan area. Attempts to apply carrying capacity concepts to urban growth management were developed in the 1970s, and have been reviewed by Godschalk (1977). IUCN, UNEP, and WWF (1991) defined sustainable development as

'*improving the quality of human life while living within the carrying capacity of supporting ecosystems*'.

Urban economic and ecological systems are physically connected by the throughput of energy and matter from natural ecosystems, and by other environmental goods and services which sustain economic activity. If

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development is to be sustainable, it must encompass a full appreciation of the value of natural and man-made environments in terms of their contribution both to present societal well-being and for intergenerational equity at local, regional and global scales.

The contributory value of an ecosystem to urban economic activity cannot be properly assessed by market prices (Costanza, 1984). Money paid for urban system resource inputs goes largely to human extractors in exchange for their work in obtaining resources, rather than being used by a form of compensation for the free work of the environmental systems that produce the resources. In both economic and ecological systems, energy is a common physical measure. When attempts are made to integrate economic and technological perspectives of systems analysis, energy terms are sometimes used. The flow and transformation of energy through the environment and within the urban ecosystem makes possible the circulation of money. However, past research projects, see for example Owens (1986), which employed energy in urban study analyses were centred on relationships between urban spatial structure and issues of energy efficiency and energy conservation.

In order to evaluate the life supporting functions of nature, analysis of the flows of energy between ecological and economic systems has emerged as a complement to economic accounting (Odum, 1971, 1988; Odum and Odum, 1981). The historical roots of energy analysis have been reviewed by Martinez-Alier (1987). The study of urban energetics has developed from the work of Patrick Geddes (1854–1932), who was one of the first authors to correlate periods of human history with experience of energy. Geddes' analysis of the evolution of cities (Geddes, 1915), based on the careful tracing out of energy flows, is regarded as being nearer to a true human ecology than that of the misnamed human ecology of Chicago urban sociology school, ca. 1920 (Martinez-Alier, 1987).

During the past 30 years, the advocacy and application of energy flows to understand the coupling of natural and socio-economic systems has been dominated by Howard T. Odum's energy school. In his book *Environment, Power, and Society,* Odum (1971) addressed the concept that power (energy flow per unit of time) from ecological systems is the energy basis of human society. Odum and Peterson (1972) related the complexity of cities to ecological principles and energy flows. Energy requirements for human beings and energy characteristics of cities based on fossil fuels were further addressed by Odum and Odum (1981). Zucchetto (1975) used the city of Miami as a case study, and developed a simulation model of urban growth based on energy flows. As a result, Zucchetto concluded that the inability of the city to capture energy and, in turn, to maximize power, leads to its decline. Using similar methods, Brown (1981) examined energy flows through the urban hierarchy in Florida. Huang *et al.* (1995) applied the ecological energetic approach to assess the ecological economic status of the Tapei metropolis and to evaluate the benefit of ecotechnology for the enhancement of environmental quality on a metropolitan scale.

Debate of the applicability of an ecological energetic approach to evaluate social systems has had a long history. Nevertheless, viewing urban systems from an energy perspective is appealing in its analogy to natural systems. The aim of this paper is to explore – using Taiwan and, specifically, the Taipei metropolis as an example – how the natural environment has contributed to the urban system and resulted in the hierarchical status and role of urban systems. Throughout this paper, the 'intrinsic' value of ecosystems in biophysical terms is emphasized, whether human preference fully recognizes that value or not.

In the first section of this paper, the urban ecosystem is described from the viewpoint of ecological economics; this is followed by the introduction to emergy (previously called embodied energy) synthesis in the methodology section. In the next section this method is applied to evaluate resource flows to and from the urban and economic systems in order to classify urban ecosystems within Taiwan and to study the energetic hierarchy of Taipei. The overall purpose of this work is to extend the results of energetic analysis of the urban system to generate insights on how to plan for an ecologically sustainable urban development.

Methodology

Assessing the intrinsic value of the natural environment in providing life-support services requires a new accounting system that can assure the contribution of a non-market oriented natural environment to the economic system. Using energy as a common numerator to evaluate the work of nature is an attractive choice in the analysis of interacting ecological and economic systems. Present work on analysing the role of the human economy as a part of the ecological system is being carried out mainly by ecologists inspired by Howard T. Odum. In an attempt to define a biophysical value theory that is applicable with equal facility to ecological and economic systems, Odum noted that all forms of energy (e.g. sunlight, fuel, electricity, etc.) do not accomplish an equivalent amount of work (Odum, 1971; 1983; 1988; Odum and Odum, 1981). Two terms—*transformity* (previously called energy transformation ratio) and *emergy* (previously called embodied energy)—were introduced by H. T. Odum in order to take into account the varied qualities of energy inherent in the hierarchy of systems components. Transformity is defined as *the ratio of energy of one type required to produce a unit of energy of another type.* Emergy is *the energy of one type required in transformation to generate a flow or a storage.* The solar emergy of a flow or storage is the solar equivalent energy required to generate that flow, or storage. Its units are solar emergy joules (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. All flows of energy can therefore be compared by expressing them in quantity of energy of one type. Non-market priced natural resources can also be evaluated. Further details on the procedure of emergy synthesis can be found in Odum *et al.* (1987), and also Huang and Odum (1991).

Data from various statistic and geographical information sources concerning Taiwan and the Taipei metropolis have been collected and assembled in order to understand their ecological economic networks, and to calculate emergy flows to and from and within the studied systems. In order to illustrate the Taiwan and Taipei's ecological economic status, emergy indices (see Table 1) can be calculated and used as variables for classification.

The multi-variate techniques incorporated in this research represent a three-step procedure utilizing both clustering and ordination techniques for the classification of ecological economics systems. First, factor analysis is used to reduce the dimensionality of the original data set by reducing the number of variables to a smaller number of factors. Second, similar units are grouped by a cluster analysis of the calculated factor scores. Finally, a discriminant analysis is used to test the heterogeneity of the initial groups and to develop classification functions to identify Taiwan's ecological economic status of various stages.

Energetic hierarchy of the Taipei metropolis

A view of the urban ecosystem as a set of energetic flows, to and from the urban system, provides a workable conceptual link between urban and natural environments. Using Odum's energy diagram, the conceptual urban ecological economic system for Taiwan can be represented by Figure 1. Energetic flows interconnect renewable sources, natural and human-subsidized ecosystems and industrialized urban systems. The renewable energy from the sun, wind, and rain not only power the two producer systems' life-support functions which in turn are transmitted to the urban system, but also provide important value to urban dwellers. Since the use of fossil energies in the urban industrial society began 200 years ago, energy and technology, imported from elsewhere, are the driving forces behind the population growth in urban areas. Exports of goods and services produced in the city are very important to the productivity of the urban economy. Through exports, the economy can exchange products made from locally abundant resources, for materials, services, and energy resources that are not so abundant. Wherever there is energy and resource consumption, as in a city, there is an accompanying production of waste. Stress caused by the inadequate treatment and accumulation of waste, affects the production

Table 1. Emergy indices for representing ecological economic interface

Name of index	Expression
Emergy sources	
Fraction of indigenous emergy used	(N0 + N1 + R)/U
Fraction of locally non-renewable emergy used	(N0 + N1)/U
Fraction of renewable emergy used	R/U
Fraction of purchased emergy used	(F + G + P2I3)/U
Fraction of free emergy used	(R + N0 + N1)/U
Fraction of imported service emergy	P213/U
Emergy intensity	
Ratio of concentrated to rural use	N1/N0
Emergy density	U/Area
Per capita emergy used	U/Pop
Per capita fuel emergy used	F/Pop
Per capita electricity used	EL/Pop
Ratio of electricity to emergy used	EL/U
Emergy structure	
Fraction of agricultural production	PR1/GDP
Fraction of manufacturing production	PR2/GDP
Fraction of service industry production	PR3/GDP
Ecological economic interface	
Ratio of export to import	(N2 + B + P1E3)/(F + G + P2I3)
Carrying capacity based on renewable emergy	R/(U/Pop)
Developed carrying capacity	8 R/(U/Pop)
Ratio of waste to renewable emergy	W/R
Ratio of waste to total emergy used	W/U
Emergy-money ratio	U/GNP
Emergy investment ratio	(F + G + P2I3 + N0 + N1)/R

B: exported products; EL: electricity used. E3: dollar in exported service; F: imported fuels; G: Imported goods; GDP: gross domestic products; GNP: gross national products; I3: dollars paid for imported service; N: indigenous non-renewable flows (N0 + N1); N0: dispersal rural (e.g. soil loss); N1: concentrated use (e.g. hydroelectricity); N2: export of raw materials; P1: emergy-money ratio; P2: world emergy-money ratio; Pop: population; PR1: agricultural productivity; PR2: manufacturing productivity; PR3: service industry productivity; R: renewable emergy flow; U: total emergy used (R + N0 + N1 + F + G + P2I3); W: waste.

and maintenance of the environmentally produced goods and services in the life-support ecosystems in a negative way. Through practices of ecotechnology (i.e. waste recycling and ecosystem reclamation) it is possible to re-invest part of the non-renewable resources and to reinforce the production potential of life-support environments (Mitsch and Jorgensen, 1989).

Evolutionary process of Taiwan's ecological economic system

In an attempt to give an overview of Taiwan's ecological economic system, Huang and Odum (1991) applied emergy synthesis to their study of Taiwan's status in terms of ecological economic interface, and the consequence of rapid economic development. In this section, the study has been revised, and data from 1960, 1970, 1980, and 1990 are used to gain a perspective on the evolving pattern of emergy uses in Taiwan (Table 2). Currently, Taiwan's ecological economic status is characterized by: (1) a large import of fuels, goods and services; and (2) a large export of manufactured goods.

In order to further investigate the evolutionary process of Taiwan's ecological economic system in a global context, emergy indices of 127 countries, originally compiled by the Center for Wetlands at the University of Florida, are used as input variables for establishing a global-wide classification of

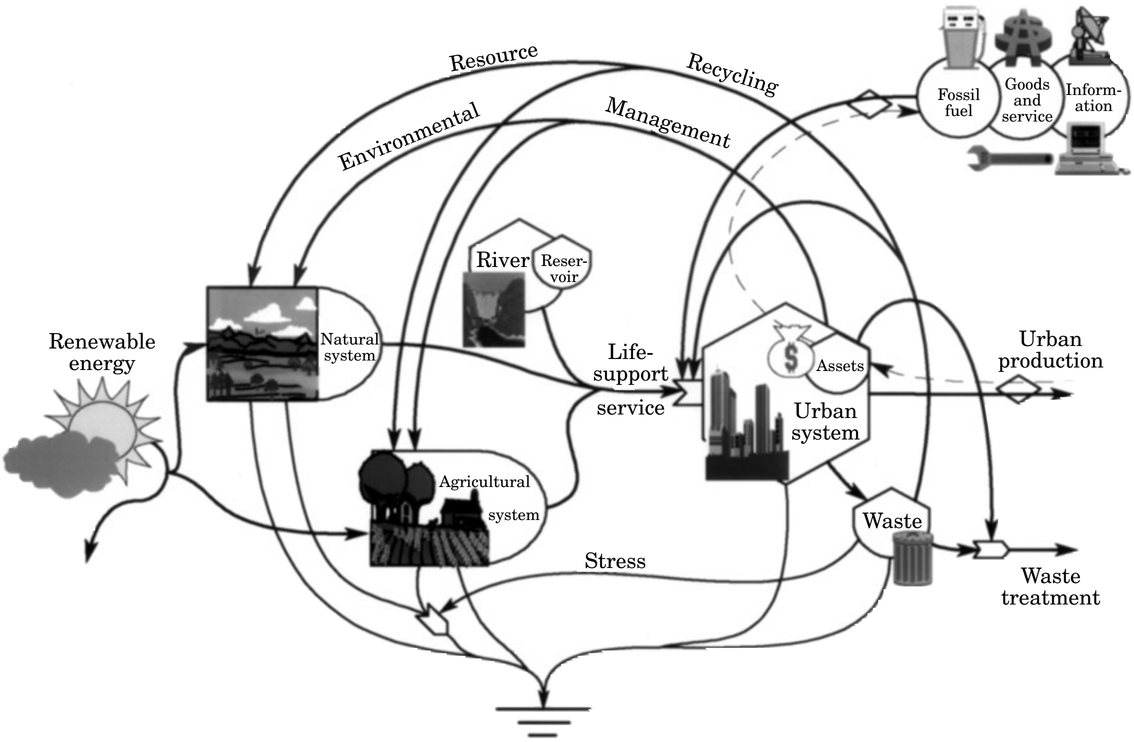

Figure 1. Energy diagram of urban ecological economic system.

Table 2. Overview of the evolving economic systems of Taiwan using emergy indices

Emergy index	Quantity			
	1960	1970	1980	1990
Renewable emergy flow; R ($\times 10^{20}$ sej/yr)	212·83	212·83	212·83	212·83
Flow from indigenous non-renewable reserves; N ($\times 10^{20}$ sej/yr)	205·40	231·88	285·83	402·20
Imported emergy flow ($\times 10^{20}$ sej/yr)	74.50	279·12	1217·40	1522·22
Total emergy used; U ($\times 10^{20}$ sej/yr)	492·73	723·83	1716·05	2137·25
Exported emergy flow ($\times 10^{20}$ sej/yr)	55·44	168·22	860·71	972·20
Fraction of indigenous emergy used	0·85	0·61	0·29	0·29
Fraction of locally non-renewable emergy used	0·42	0·32	0·17	0·19
Fraction of renewable emergy used	0·43	0·29	0·12	0·09
Fraction of purchased emergy used	0·15	0·39	0·71	0·71
Fraction of free emergy used	0·73	0·49	0·21	0·17
Fraction of imported service emergy	0·04	0·11	0·13	0·24
Ratio of concentrated to rural use	0·38	1·04	3·79	5·02
Emergy density ($\times 10^{12}$ sej/m^2.yr)	1·37	2·01	4·77	5·94
Per capita emergy used ($\times 10^{20}$ sej/person.yr)	4·42	4·93	9·64	10·60
Ratio of electricity to emergy used	0·04	0·10	0·13	0·20
Ratio of export to import	0·74	0·60	0·71	0·64
Carrying capacity based on renewable emergy ($\times 10^6$ person)	4·82	4·31	2·21	1·00
Developed carrying capacity ($\times 10^6$ person)	38·50	34·50	17·70	16·00
Ratio of waste to renewable emergy	0·33	0·74	1·42	2·89
Ratio of waste to total emergy used	0·14	0·22	0·18	0·29
Emergy-money ratio ($\times 10^{12}$ sej/\$)	31·50	12·80	41·40	13·50
Emergy investment ratio	1·32	2·40	7·06	9·04

Table 3. Factor loading matrix of 127 countries for world ecological economic classification

Variable	Factor		
	I Emergy source	II Emergy intensity	III Emergy welfare
Fraction of locally non-renewable emergy used	**0·952**	−0·047	0·022
Fraction of free emergy used	**0·951**	−0·055	0·018
Fraction of purchased emergy used	−0·885	**0·191**	−0·022
Fraction of indigenous emergy used	**0·881**	−0·192	0·021
Ratio of electricity to emergy used	−**0·760**	−0·202	0·243
Fraction of imported service	−**0·757**	0·351	−0·144
Emergy-money ratio	**0·615**	0·144	0·025
Emergy investment ratio	−0·053	**0·972**	0·045
Emergy density	0·027	**0·968**	0·040
Ratio of concentrated to rural use	−0·088	**0·948**	0·046
Per capita emergy used	0·165	0·129	**0·774**
Ratio of export to import	0·155	0·026	−**0·625**
Eigen value	4·961	3·060	1·078
Total variance (%)	49·04	19·57	8·78
Cumulative total variation (%)	49·04	68·61	77·39

ecological economic systems. Factor analysis is used to reduce the dimensionality of the original 12 emergy indices into the present three factors, which explain 77·4% of the variation in the original data set. The relationships between these three factors and the original variables are listed in Table 3. Factor I summarizes emergy indices related to source of emergy flow, and can be interpreted as emergy source. Factor II is strongly related to emergy intensity. Factor III is associated with indices of per capita emergy used and export-import ratio, and can be interpreted as a welfare factor.

Estimated factor scores of the three extracted factors for the 127 countries are calculated and used as input for the subsequent cluster analysis in order to establish the hierarchical system of world ecological economic classification (Figure 2). In order to decide which of the classification types Taiwan's ecological economic system belongs to, and in order to reveal its stage of evolution, a discriminant analysis was performed to develop functions for classifying Taiwan's ecological economic system, in 1960, 1970, 1980, and 1990. As a result, Taiwan's ecological economic system was characterized as a less developed country in 1960, industrial transitional country in 1970, and highly industrialized country in 1980 and 1990.

1960—less developed country

According to the characteristics of the established world ecological economic system, a less developed country is characterized by its high reliance on renewable emergy. During the period of 1953 to 1960, the economic development in Taiwan was carried out mainly through US Aid. A major focus of development was placed on the agricultural sector for the purpose of stabilizing the national economy, and to lead to the creation of an industrialized society. In 1960, the contribution of rural emergy (R) to the entire ecological economic system in Taiwan was equivalent to 43·19% of the total emergy used (U). On the contrary, the percentage of the imported emergy was only 15% of the total emergy used. Due to the relatively small quantity of total emergy flow, as compared to later stages, the emergy density and per capita emergy used were considerably small. High contribution from renewable emergy, low emergy investment

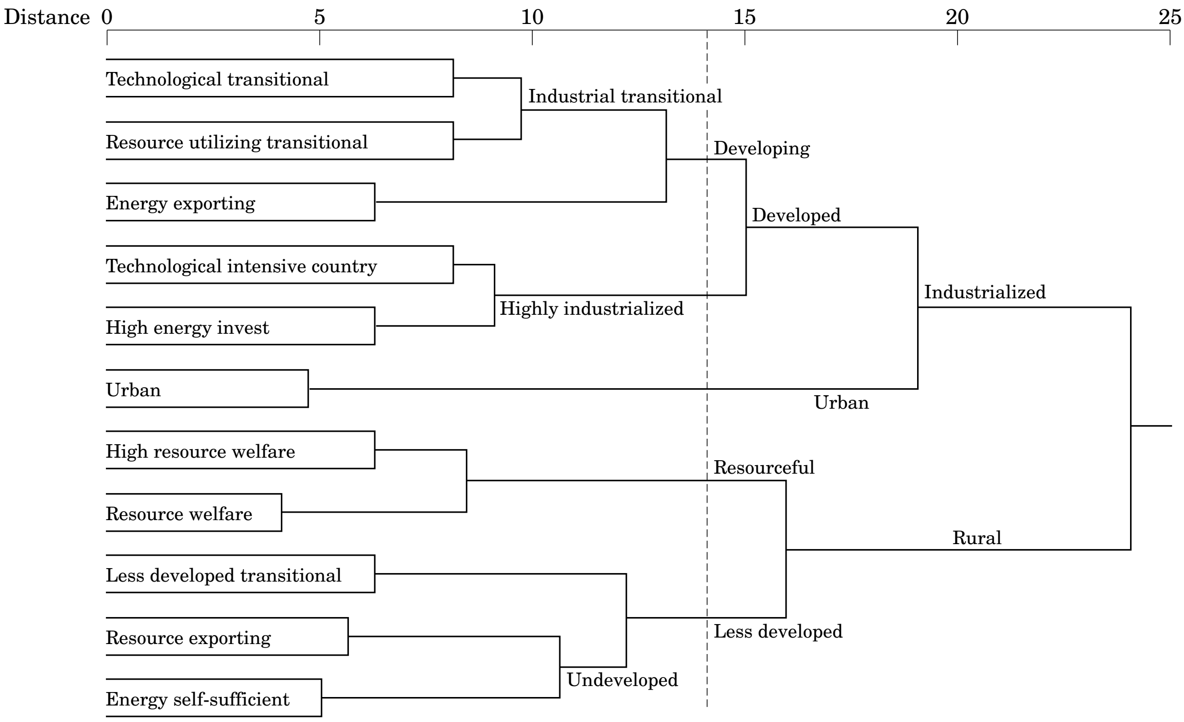

Figure 2. World classification of ecological economic system.

ratio, and a high self-sufficiency in emergy use represented the rural characteristics of Taiwan in 1960.

1970—industrial transitional country

During the period from 1961 to 1972, the national policy of Taiwan was focused on economic development for the expansion of foreign trade. The quantities of imported and exported emergy flows increased to a level three times greater than in 1960. The emergy contribution from the rural environment to Taiwan's ecological economic system decreased, and was subsequently substituted by purchased emergy. This stage represented Taiwan's transition from a rural society to a developed country.

1980—highly industrialized country

Taiwan made remarkable improvements in its economy during the period from 1970 to 1980. The major economic policy promoted stabilizing and modernizing economic growth in order to improve living standards. Under the influence of technological improvements in agricultural production, surplus labour from the agricultural sector was re-allocated to manufacturing and industrial sectors. Due to the change in economic structure, imported emergy increased significantly from $279{\cdot}12 \times 10^{20}$sej in 1970, and then to $1{,}217{\cdot}4 \times 10^{20}$sej in 1980. Exported emergy also increased more than four times from $168{\cdot}22 \times 10^{20}$sej in 1970, and then to $860{\cdot}71 \times 10^{20}$sej in 1980 due to the expansion of foreign trade. The fraction of indigenous emergy used decreased from 0·61 to 0·29. The high emergy investment ratio (7·06) signified Taiwan's developed stage in 1980.

1990—highly industrialized country

Based on the world classification system presented in Figure 2, Taiwan was placed under the same category in the ecological economic system as a highly industrialized country as in 1980. As indicated in Table 2, the emergy indices followed the pattern of 1980, with slight increases in total emergy used and intensity. The contribution from renewable sources dropped to less than 10%; the

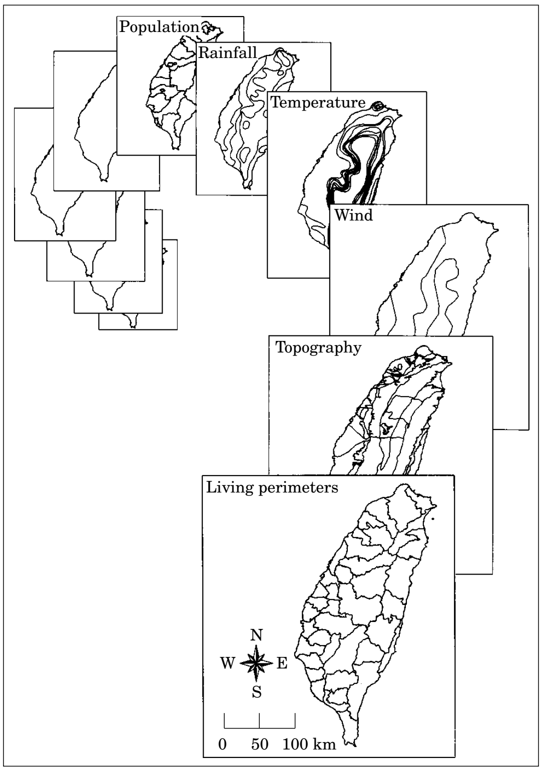

Figure 3. Natural energies and socio-economic data of Taiwan.

fraction of free emergy used also decreased from 0·21 to 0·17. Signs of increasing pressure from the economic system to the natural environment are revealed by indices related to waste concentration. The emergy investment ratio also increased, indicating the lack of emergy fed back from economic system to reinforce the production potential of natural environment.

Classification of Taiwan's urban ecological economic system

Stimulated by large inputs of auxiliary energy in the form of fossil fuels, electricity, and goods and services, urban areas may prosper, but this sometimes also leads to the depletion of natural capital stocks. As a result, different energy structures, and subsequently different types and amount of energy flows tend to associate with different stages and intensities of urbanization. For a densely populated country such as Taiwan, urbanization could not be sustained without substantial imports of energy and matter from outside ecosystems.

Most of Taiwan's population is concentrated along its western coastline. Until very recently, the smaller inland cities were rural centres predominantly associated with agriculture. Now, with the development of the economy through expansion of foreign trade, those same small cities have become industrialized centres, and both populations and assets have grown significantly. In order to identify how energy flows vary spatially due to natural environmental and urbanization factors, a taxonomic approach is used to classify the land units of Taiwan objectively into homogeneous zones within the ecological economic system. As shown in Figure 3, the island of Taiwan, encompassing 36 000 km^2, is divided into 39 districts of living perimeter on the basis of daily commuting distance. The rationale supporting the concept that the living perimeter can be viewed as an urban ecosystem, and used as a classification unit is that an urban core exists within each unit and energy from rural areas

Table 4. Rotated factor loading matrix in the 39 districts of Taiwan for ecological energetic classification

	Factor			
Variable	I	II	III	IV
Fraction of locally non-renewable emergy used	**0·94194**	−0·16451	−0·11853	−0·06869
Fraction of indigenous emergy used	**0·93446**	−0·22007	−0·16772	−0·01651
Per capita emergy used	**0·88462**	−0·03585	−0·05415	−0·17670
Ratio of concentrated to rural use	**0·86743**	−0·02061	−0·08785	−0·17557
Developed carrying capacity	**0·73893**	−0·08086	−0·00705	0·07516
Ratio of waste to total emergy used	−**0·89406**	0·03180	−0·24754	−0·06599
Ratio of electricity to emergy used	−**0·95657**	0·01710	0·06456	−0·18321
Ratio of purchased to free emergy used	−0·10804	**0·97525**	0·09903	−0·03420
Emergy investment ratio	−0·12810	**0·96964**	0·07179	−0·07684
Emergy density	−0·05358	**0·95148**	0·15600	0·06230
Ratio of waste to renewable emergy	−0·23003	**0·93074**	0·02223	−0·13019
Per capita electricity used	−0·11853	0·21822	**0·94644**	0·04486
Fraction of manufacturing productivity	−0·08980	0·02781	**0·93505**	−0·25732
Fraction of agricultural productivity	−0·23758	−0·42987	−**0·63864**	−0·25066
Carrying capacity based on renewable emergy	−0·17254	−0·22609	−0·04956	**0·73942**
Per capita fuel emergy used	−0·04288	0·46251	0·38614	**0·58270**
Fraction of service industry productivity	−0·32994	0·36661	−0·53770	**0·54489**
Fraction of renewable emergy used	0·03746	−0·46628	−0·27840	**0·51234**
Eigen value	5·8601	4·5980	2·8542	1·7153
Total variance (%)	32·52	25·54	15·86	9·53
Cumulative total variation (%)	32·52	58·06	73·92	83·45

converge spatially to urban cores. Natural factors such as solar insolation, annual rainfall, wind and elevation, which are related to flows of renewable energy sources were collected and mapped. Socio-economic data for interpreting the consumption of non-renewable energies, imports of goods and services and the generation of wastes, have also been estimated for each district of living perimeter. Emergy synthesis was then performed and emergy indices shown in Table 1 were calculated for each individual district of living perimeter.

Factor analysis was initially used to reduce the dimensionality of the data. A reduction from 18 variables to four factors was achieved through extraction and rotation of the factor loading matrix. The relationships between the rotated factors and the original variables are listed in Table 4. Factor I is most strongly associated with variables 'fraction of non-renewable emergy used', 'fraction of indigenous emergy used', 'per capita emergy used', 'ratio of concentrated to rural use', etc. and can be interpreted as high self-sufficient emergy structure. Factor II summarizes variables related to the match between emergy from economic system and natural system and therefore is a factor of heterotrophic urban emergy structure. Factor III is predominantly related to electricity use and productivity of manufacture, and can be interpreted as a factor of rural manufacturing industry. Factor IV is a resource welfare factor because the renewable carrying capacity variable loads heavily upon it.

Estimated factor scores of the four extracted factors were used as input for an initial grouping of 39 districts of living perimeter into various zones of urban ecological economic systems. The hierarchical clustering technique was chosen to combine 39 districts into successive larger groups based on their overall similarity. The calculated

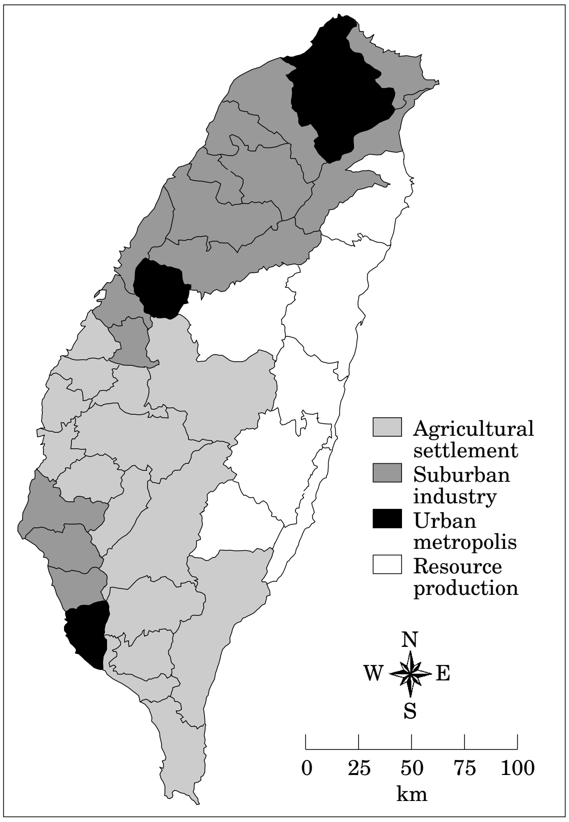

Figure 4. Geographical distribution of four urban ecological economic system.

variables suggest that four groups would be a plausible grouping number to represent the different urban ecological economic systems of Taiwan geographically (see Figure 4).

The zone of agricultural settlement is characterized by a higher self-sufficient emergy and a lower purchased emergy from the economic system. This zone is located predominantly on the south-western portion of the island. There are three districts of living perimeter classified as urban metropolis in Taiwan: Taipei, Taichung, and Kaohsiung. The energy inflows of urban metropolis rely mainly on imported/purchased energy. The emergy investment ratio, emergy density and waste production among the four zones is the highest here. The zone of suburban industry is located mainly in the north, close to the urban metropolis of Taipei. This zone also has a low self-sufficiency in terms of emergy use. The resource production zone has a very high reliance on indigenous emergy and can be considered the least developed zone in Taiwan. The resource production zone lies mainly on the eastern part of the island. The characteristics of each zone of urban ecological economic system are also summarized in Table 5.

Taipei – the energy convergent centre of Taiwan

Based on Taiwan's urban ecological economic system classification, the Taipei metropolis is one of the most highly developed districts. The most serious problems associated with urban development are: (1) the loss of life-support environments (e.g. prime agricultural land) due to the conversion to buildings, roads etc.; and (2) waste generation, discarding instead of recycling for productive purposes. Huang and Chen (1990) developed a systems model to analyse the environmental carrying capacity of the Taipei metropolis. Their results suggested that Taipei's urban growth will be significantly constrained by its environmentally sensitive areas, and the availability and capacity of its water supply system and waste treatment

Table 5. Summary of the characteristics of each urban ecological economic system in Taiwan

Characteristics	Zone			
	Agricultural settlement	Suburban industry	Urban metropolis	Resource production
Emergy sources				
Fraction of indigenous emergy used	low	very low	lowest	very high
Fraction of locally non-renewable emergy used	med	low	very low	very high
Fraction of renewable emergy used	med	low	very low	med
Fraction of purchased emergy used	low	med	very high	low
Emergy intensity				
Ratio of concentrated to rural use	very low	low	low	high
Emergy density	low	med	high	low
Per capita emergy used	low	low	low	high
Per capita fuel emergy used	med	med	high	low
Per capita electricity used	low	med	med	low
Ratio of electricity to emergy used	high	high	high	low
Emergy structure				
Fraction of agricultural production	high	low	very low	med
Fraction of manufacturing production	low	high	med	med
Fraction of service industry production	low	low	high	low
Ecological economic interface				
Carrying capacity based on renewable emergy	med	low	low	very low
Developed carrying capacity	med	low	med	high
Ratio of waste to renewable emergy	low	med	high	very low
Ratio of waste to total emergy used	high	high	high	very low
Emergy investment ratio	low	high	very high	low

facilities. In order to assess the benefit of an ecological engineering approach for assessing the environmental quality of the Taipei metropolis, Huang *et al.* (1995) conducted an emergy synthesis. The results indicated that the Taipei metropolis operates its activities mainly on imported fuels and goods and services, which account for 90% of total emergy used.

Taipei, the downtown urban core of the Taipei metropolis, was once a city whose support was based on the rich environmental resources of the surrounding local metropolis. In the last 20 years however, Taipei has emerged as an international city with much of the island of Taiwan acting as its support region. The comparison of emergy indices between the Taipei metropolis and the city of Taipei (Table 6) further indicates that Taipei's energy hierarchical position is higher than that of the Taipei metropolis as a whole.

In summary, energy converges from zones of agricultural and resource production to zones of suburban industry and urban metropolis, finally moving towards urban centres, such as Taipei. Although the urban centre is capable of attracting a significant amount of energy to support its activities, the system has become more dependent on external inputs of energy. Hence, due to the separate administrative boundaries, Taipei

Table 6. Comparison of emergy indices of Taipei city and Taipei metropolis in 1990

Index	Taipei City	Taipei metropolis
Ratio of concentrated to rural use	0·125	0·23
Emergy density ($\times 10^{14}$ sej/m^2.yr)	1·27	0·43
Per capita emergy used ($\times 10^{16}$ sej/person.yr)	1·28	1·43
Ratio of waste to renewable emergy used	54·33	15·38
Emergy-money ratio ($\times 10^{12}$ sej/\$)	1·19	1·33
Emergy investment ratio	214·61	66·14

city has also become much more difficult to predict, exploit and manage in a sustainable fashion.

Concluding remarks and future research

Previous studies on urban systems have focused mainly on socio-economic perspective. Using ecological energetic approach, this paper is a continuing effort of Huang and Odum (1991) to investigate the evolutionary process of Taiwan's ecological economic status and to classify Taiwan's urban ecological economic systems. Using emergy evaluation, it is quite clear why manufacturing and export of merchandise since 1960s has caused prosperity and rapid growth in Taiwan. In less than half a century, Taiwan has changed from a rural island with an economy based on raw commodity production, to a developed country with many large urban centres. Because of its highly industrialized status (high emergy-money ratio), Taiwan can no longer rely on labour-intensive manufacturing activity; the national economy is currently trying to restructure to shift from labour-intensive industry to high-technological based industry.

The distribution of the four urban ecological economic systems reveal the spatial energetic hierarchy within Taiwan. Three urban metropolis have formed on the west coast of the island, representing Taiwan's highest levels within the urban ecological economic system hierarchy. Much of the growth of Taiwan's urban centres is the direct result of increased fuel supplies. While the renewable energies of sun, wind, rain and tides are important, and were a key factor in early settlement and growth, it is the increase in imports of fossil fuels, goods and services that has made much of the development of Taiwan possible. The quality of life is not solely dependent on the quality of the urban environment, but also on a healthy environment in non-urban regions which the urban areas depend on for their resource inputs that sustain them. In order to balance the relationship between people and nature and to enhance the quality of life for the inhabitants of Taiwan, a return from the economy must be made to maintaining the life-support systems by, for example, watershed protection, rebuilding soils or nutrients soils or nutrient recycling.

Energy measures are useful for identifying, mapping, and evaluating instrumental values in ecological and economic systems. This paper provides a useful first step in the application of ecological energetic analysis for understanding the urban ecological and economic systems as a single entity. The continuing application of the emergy concept for urban ecological economic systems raises several possible questions and directions for discussion:

(1) How do different ecological economic zones within an urban system interact and self-organize in a symbiotic way during the evolutionary process?
(2) What are the energy characteritics of the different land uses of Taiwan and what are the implications to land use planning and management. For example, this would involve the study of the spatial allocation and arrangement of land use activity in relation to patterns of energy flows.
(3) How can GIS be used to display the spatial distribution of energy flow within an urban system? Such work would use

the cartographic modelling capabilities of GIS to study how energy converges in the spatial context.

(4) What is the optimal or plausible energy matching between urban economies and natural systems? How should we go about measuring the ecological footprint (see Rees and Wackernagel, 1994) for an urban centre such as Taipei?

Research is required in each of these areas.

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