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Energy hierarchy and urban landscape system

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Abstract

The study of ecosystems suggests principles by which the flow of energy generates hierarchies in all systems. From viewpoint of ecological energetics, urban system lies on the highest level of ecosystem hierarchy. The main objective of this paper is to study the effect of energy flows on the hierarchies and spatial organization of urban zonation. This research uses Taipei metropolitan region as the area for the case study. ‘‘Emergy’’ is used as the principal conceptual tool for energy analysis; ‘‘transformity’’ is used to measure the hierarchies of land uses and urban landscape systems. Based on the calculation of the spatial distribution of energy flows, using GIS, the empower density and transformity increase from rural to urban center. In order to delineate zones of different energetics, the 1178 administrative districts of the Taipei metropolitan region are used as units for multivariate classification, in which 19 variables of energy flows are condensed into four factors. The factor scores of each districts are then used as input for cluster analysis and discriminate analysis. As a result, different energy structures, and subsequently, different types and amount of energy flows tend to associate with different intensities of urbanization. The Taipei metropolitan region is classified into six energetic zones: mixed-use urban core; high density urban residential district; service and manufacturing urban district; agricultural district, newly developed suburban district; and natural area. The calculation of transformity and emergy indices further establish the hierarchical order of these zones. The distribution of the six energetic zones, reveals the spatial energetic hierarchies of Taipei metropolitan region. The implication of energetic characteristics to planning practice is also discussed to conclude this research. © 2001 Published by Elsevier Science B.V.

Keywords: Emergy; Energy hierarchy; Multivariate analysis; Taipei metropolitan region; Transformity; Urban ecosystems; Urban zonation

1. Introduction

Energy is required for all the processes in the ecosystem; this energy comes from the sun as light and is received on earth, where it heats water, produces plant food, and indirectly generate winds, waves, and fossil fuels in the ground. As energy flows and gets transformed on the earth, a hierarchy of trophic levels is formed, which functions differently in a system. Due to the spatially variant characteristics of the natural environment, the different types and amount of energy received on the earth are not homogeneous which thus generates a spatial pattern of landscape. Based on the types and the amount of energy available, Odum (1989) has classified ecosystem into four types: unsubsidized natural solar-powered; naturally subsidized solar-powered; human-subsidized solar-powered; and fuel-powered urban-industrial. The urban area is in some sense a

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heterotrophic system that has to rely on the surrounding landscapes for life support services.

Modern cities are characterized by marked evolutionary changes, in which a profound effect is exerted by the energy flows to and in the city. The urban economic and ecological systems are physically connected by the throughput of energy and matter from the natural ecosystems which sustain economic activity, while on the other hand by the goods and services from the economic system which augment life support functions of the ecosystem. The approach of urban metabolism has been proposed by many urban studies over the past 30 years to assess the consequential environmental effects of urbanization (see Wolman, 1965; Boyden et al., 1981; Douglas, 1983; Girardet, 1996). Like human body's metabolism, the physical and biological process in a city system transform inflows of energy and materials into useful products, services, and wastes. Newman (1999) further expand the concept of urban metabolism to include aspects of livability for demonstrating the practical meaning of sustainability. White (1994) suggested that energy analysis can be incorporated to study a city's metabolism. Energy can be considered as a common denominator for all processes in the ecosystem, including human economic system. Martinez-Alier (1987) addressed the merit of Geddes' idea of carefully tracing out the energy flows to analyze the evolution of cities (Geddes, 1915), which is closer to the true human ecology than the misnamed "human ecology" of the school of urban sociology of Chicago in the 1920s. Unfortunately, the current research on urban form have paid little attention to urban energetics. The earlier research on the hierarchically organized urban system used entropy-maximizing paradigm, which assumes the society to be a closed system (Batten, 1982). Haines (1986) reviewed research on the investigations of the relationship between efficiency of fossil fuels consumption and spatial configuration of the urban form. Energy indices such as per capita fuel energy use has been proposed by Newman and Kenworthy (1999) to assess the sustainability of cities. However, the importance of an energy theory and research for investigations on a relationship between energy flows and urban form is ignored.

In an effort to explore how the natural environment has contributed to an urban system which has resulted in its hierarchical role, Huang (1998a) has performed an energy evaluation of Taiwan to study its changing ecological economic status. The urban ecosystems were classified into four types to show the spatial energetic hierarchy within Taiwan. In order to study the evolution of urban ecosystems, Huang (1998b) has developed a system model to simulate the evolution of urban zones in relation to energy flows. Five consecutive zones were hypothesized to represent Taipei metropolis' spatial configuration, but the spatial data were not incorporated for the analysis. The main objective of this paper is to further devise an urban zonation system of the Taipei metropolitan region by demonstrating that the energy flows, from the viewpoint of ecological economic system, could reveal a spatially hierarchical order of an urban landscape system. The term "urban" refers, in this paper, to a functionally interwoven agglomeration, comprising of a central city with surrounding areas which provide life support services to the city in that context. In order to study the urban spatial structure from the ecological economic perspective, Odum's energy school will be introduced in this paper. The terms "transformity" and "emergy", initiated by Odum (1988), will be used as the principal conceptual tool for energy analysis to express the phenomena of energy flows in the combined system of man and nature. The primary aims of using the concept of emergy synthesis to study the urban spatial structure of Taipei are as follows:

1. to display the spatial distribution of each energy flows, including energy sources from both natural systems and human economy;
2. to study the energy hierarchies of each land use in Taipei metropolitan region and reveal their spatial hierarchies;
3. to develop an energetic zonation to display the spatial hierarchy of an urban landscape system;
4. to discuss the implication of energy flows for planning and management of urban development.

Section 2 introduces emergy concept on a theoretical basis for revealing hierarchy of land uses and the multivariate techniques for delineating zones of ecological energetics. In the following sections, these methods are applied to analyze the energy hierarchy of land uses in Taipei metropolitan region and to study its urban spatial structure with respect to ecological energetics. Thereafter, the implication of energetic zonation in the planning and management of urban development is discussed.

2. Methodology

In an attempt to define the theory of biophysical value that is applicable with equal ease to ecological and economic systems, Odum noted that all forms of energy (e.g. sunlight, water, fuel, etc.) do not accomplish an equivalent amount of work. Based on the general system principles and laws of thermodynamics, Odum has formulated a unifying theory of systems ecology of values (Odum, 1971, 1988, 1996; Odum and Odum, 1981). A lower quality of energy (e.g. sunlight) is transformed to a higher quality (e.g. human services) in less quantity because energy is degraded during the transformation process — second law of thermodynamics. In order to take into account the varied qualities of energy inherent in the hierarchy of systems components, two terminologies — emergy (previously known as embodied energy) and transformity (previously called energy transformation ratio) — were initiated by Odum and defined as follows (Odum, 1996):

Emergy (spelled with an 'M') — all the available energy that was used in the work of making a product and expressed in units of one type of energy.

Transformity — the emergy of one type required to make a unit of energy of another type.

Since everything is related to everything else, according to the amount required to generate, the more energy transformation steps, the higher is the transformity. For example, since four units of coal energy (cej; coal equivalent joules) are required to generate 1 J of electricity energy, the coal transformity of electricity is 4 cej/J. Transformity measures relative position in a scale of increasing quality of energy. In other words, there is a hierarchy of energy.

Solar emergy of a flow or storage is the solar equivalent energy required to generate that flow or storage. It is denoted by the unit solar emergy joule (sej). After the energy content (e.g. joule) of a flow has been estimated, it can be multiplied by its solar transformity (sej/J) to obtain its solar emergy:

$$\text{Solar emergy (sej)} = \text{energy (J)} \times \text{solar transformity (sej/J)}$$

The emergy production and use per unit of time is called empower. For example, the total emergy use per year is the annual empower of a city. Emergy and empower include all inputs, fuels, electricity, environmental, people, etc. Emergy indices such as empower density (emergy/area per time), fraction of indigenous emergy used, emergy investment ratio (emergy inputs from nonrenewable sources and economic system/ emergy inflows from renewable energy), etc. can be calculated to illustrate the ecological-economic interface. A more detailed procedure of emergy synthesis can be found in Odum (1996) and Huang and Odum (1991). The emergy concept offers a complementary viewpoint on the value of biophysical nature of human activity. It broadens the perspective to include the work of the natural environment.

The underlying theme in this paper is the hypothetical effect of energy flows on urban zonation, and how different zones organize hierarchically in the spatial context. Moss (1983) has suggested the incorporation of land process data for classifying a landscape into various zones. The basic premise of land process is that any unit of land is an open system with inflow and outflow of energy and material. But the development of a land classification system, on the basis of ecological energetics has seldom been addressed. The Taipei metropolis, situated in the northern region of Taiwan, encompassing 1724 km^2, includes 1178 administrative districts. The delineation of different urban zones to study the energy hierarchy of the Taipei metropolitan region is of a multivariate nature in which it seeks to analyze many attributes that are measured for each administrative districts. A taxonomic approach was used to objectively classify the administrative districts into homogeneous zones to study the spatial energetic hierarchy of the metropolis. The multivariate techniques incorporated in this study represent a three-step procedure utilizing both clustering and ordination techniques:

1. *Factor analysis*: This ordination technique is used to reduce the dimension of the original data set by reducing the number of variables to a smaller number of factors. The factor loadings, which are correlations between the original variables and the new factors, are then used to calculate the factor scores of each district along each factor to replace the original variables for subsequent analysis.

2. *Cluster analysis*: Similar administrative units are grouped together in the cluster analysis by the calculated factor scores. The advantage of using factor scores rather than the raw data is to clarify the relationships between measured characteristics and mitigate the effect of redundant or correlated variables.
3. *Discriminant analysis*: This ordination technique exemplifies a multivariate statistical method to validate the delineated zones. The heterogeneity of the initial groups is tested using discriminant functions, and the administrative districts are reclassified using the established classification functions.

Data from various sources of geographical or economic information and statistics of the Taipei metropolitan region are collected and interpreted to: (1) calculate and display the spatial distribution of energy flows within the metropolitan region; (2) estimate the land use transformity on the spatial scale; and (3) classify Taipei metropolitan region into different zones based on the types and amount of energy flows. In order to study the spatial hierarchy of the study area, a geographic information system is used to analyze the relationships regarding the distribution of energy flow with land uses, wherein the 1178 administrative districts are used as units for classification. To show the spatial pattern of emergy use, annual empower density (emergy flow per area) is used for all emergy flows.

3. Energetic hierarchy of land use

Hierarchy theory allows the decomposition of a complex system into an interconnecting components. Objects or matter can be arranged in a series according to the number of transformation steps required from one item to another. According to the second law of thermodynamics, the ability of energy to do work is degraded in any energy transformation. With the concept of transformity, we have a scale of energy quality that indicates the position in the energy hierarchy: the greater the quality of energy, the greater is the transformity; its energy hierarchy is also higher. Odum et al. (1995) suggested that this energy hierarchy also explains the spatial pattern of the landscape; wherein the urban and information center lies on the highest level of hierarchy. Fig. 1 illustrates the conceptual relation between energy flows and spatial hierarchy in an urban landscape, where the natural process of wind, water, and earth converge, and the transformities and concentrations of resources increase. As the energy from life support and produc-

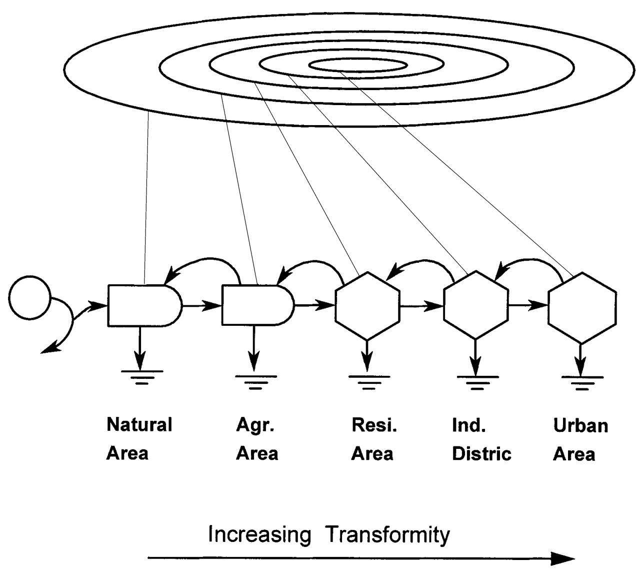


Fig. 1. Energy flows and urban hierarchy.

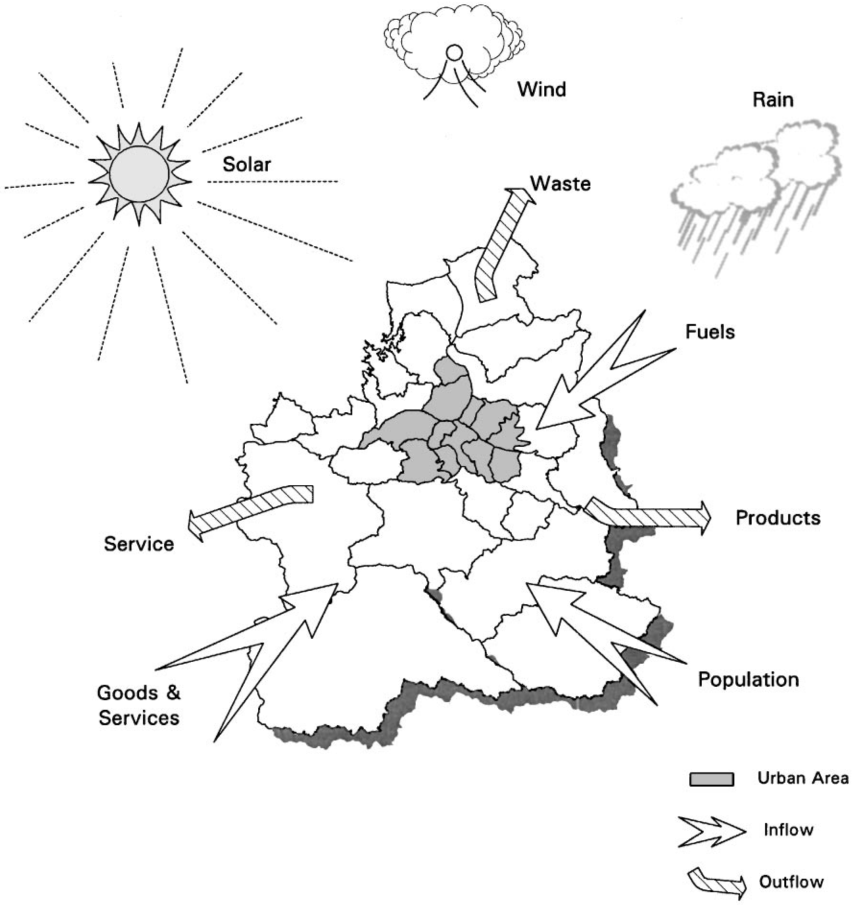
tion systems transform and converge toward consumer centers, the transformity increases with each step from geographically dispersed small units to more centralized units. The spatially converging pattern of energy flow brings in highly concentrated flows of high energy into the centers. Since production and consumption are symbiotic, the services (e.g. labor, management) and valuable products (e.g. machinery, fertilizer, etc.) diverge from urban centers as they are recycled, stimulating production of food and other physiological necessities at the lower hierarchy. In this aspect, urbanization can be seen as the process of change in the type of energy sources, which tend to increase the intensity of energy convergence from the surrounding landscapes.

The city of Taipei is located in the central portion of the Taipei Basin (Fig. 2), the lowest part of the Tamsui River watershed; the physical energy of water running downhill was used to spread water and nutrients out in flood plains, and marshes, where it stimulated agricultural productivity of the land in the past. The existence and maintenance of the city and its internal structure depend on the flow of goods and services in, out and throughout the city. Flowing into the city, we have, food, fuels, raw materials, water, labor, etc. and flowing out we find services, finished products, wastes, etc. The renewable energy from the sun, wind, and rain not only power life support functions which in turn are transmitted to the urban system, but also provide important value to the urban dwellers. Energy and technology, imported from elsewhere, are the driving forces behind the population growth in urban areas. The flow and transformation of energy through the environment and within the city makes possible the circulation of money and economic activities. Exports of goods and services produced in the city are very important to the productivity of the urban economy through exchange of products for materials, services, and energy resources that are not so abundant. Wherever there is a consumption of energy and resource, as in a city, there is an accompanying production of waste.

Transformity for measuring the hierarchy of land use can be calculated by summing all emergy flows during the past two hundreds years and then divided by its current potential energy (see Fig. 2). The turnover time for each energy flows vary according to the type of land use it flows in (see Table 1). The potential energy of land use is calculated by estimating the mass on the surface (e.g. biomass, structure, etc.), which is then converted to energy unit in Joule. In order to explore the spatial energetic hierarchy of Taipei metropolitan region, each energy flows, ranging from renewable, non-renewable, to economic inputs were compiled using GIS. Fig. 3 displays the distribution of total renewable emergy density, total emergy density of economic inputs, potential energy of land use, and the calculated transformity of the Taipei metropolitan region. The spatial distribution of transformity and the concentration of emergy flows per unit area were also evaluated for transacts (Fig. 4). The surrounding landscape of Taipei metropolitan region is characterized by hilly slopes and forest, which receives highest renewable emergy flow while the inner area where Taipei city is located has higher emergy flows of non-renewable sources and economic inputs. Transformity increases toward the center of hierarchy and it also increases with the total emergy inputs to an urban system. The higher transformity in the urban area coincides with the hypothesis that energy converge spatially toward consumer center. Table 1 summarizes the average emergy density, turnover time, potential energy and transformity of each land use in the Taipei metropolitan region. Stimulated by large inputs of auxiliary energy in the form of fossil fuels, electricity, and goods and services, the land uses in urban areas (e.g. residential and commercial districts, etc.) of the Taipei metropolis prosper and have the highest transformities. On the contrary, natural areas such as forest, wetlands, and grassland have the lowest transformities, and represent the lowest hierarchy in the landscape.

4. Energetic zonation and urban spatial structure

From an ecological perspective, boundaries between land units are set to a large degree by an interaction of energy of various forms (e.g. solar, moisture, nonrenewable, etc.) within the defined area. Energy flows is a basic functional characteristic of the ecosystem; it also serve as a measure for understanding man and his environment. The study of ecosystem suggests principles by which the flow of energy generates hierarchies in all systems. The spatial organization of cities in the landscape is often represented as a



$$\text{Transformity} = \frac{(\sum R_i * T_R) + 1/2(\sum F_i * T_F)}{E_L}$$

R_i : Renewable emergy *i*

F_i : Emergy flow of non-renewable and economics *i*

T_R : Turnover time of renewable flow

T_F : Turnover time of non-renewable flow

E_L : Potentical energy of land use

Fig. 2. Urban energetics of Taipei.

hierarchy. One reason for the hierarchical organization of cities in the landscape is for distribution of goods and services as described by Friedman (1973), and the other reason for this hierarchy is the convergence of energy (Odum, 1988). However, not only are the cities organized in hierarchies, but each city with its surrounding landscapes is also arranged in a spatial hierarchy. Concentric-circle model, sector model, and multi-nuclei model have been used extensively to describe urban spatial structure with central business district (CBD) in the center (see Miller, 1988). Major factors determining the spatial character of a city are rate of population growth, transportation, and economic status, etc. It has also been hypothesized that the spatial configuration of human activities depends largely on energy production and the con-

Table 1
Empower densities, turnover time, and transformity of each land use in Taipei metropolitan region

Land use type	Renewable emergy		Non-renewable emergy and economic input		Total empower density (10^{12} sej/m^2)	Potential energy (10^6 J/m^2)	Solar transformity (10^6 sej/J)
	Empower density (10^{12} sej/m^2 per year)	Turnover time (year)	Empower density (10^{10} sej/m^2 per year)	Turnover time (year)			
Forest	60.44	100.00	0.00	0.00	60.44	210.00	0.29
Grassland	36.65	5.00	0.00	0.00	1.83	12.70	0.14
Wetland	33.42	10.00	0.00	0.00	3.34	44.00	0.08
Farm	27.55	20.00	11.75	10.00	123.01	31.90	3.85
River	26.96	1.00	0.00	0.00	0.27	480.00	–[a]
Low density residential	41.30	200.00	1618.68	25.00	78387.10	640.00	122.00
Medium density residential	40.78	200.00	5879.30	50.00	579592.56	1290.00	151.00
High density residential and commercial	42.70	200.00	8158.22	100.00	1129746.40	3020.00	207.00
Industrial	41.99	200.00	1828.91	55.00	181838.08	2250.00	79.80
School	45.81	200.00	1697.60	70.00	166515.22	1200.00	98.00
Institutional	45.32	200.00	1420.79	81.00	232648.12	2250.00	107.00
Utility	45.90	200.00	692.58	65.00	105715.50	1150.00	96.30
Transportation	22.21	200.00	1856.02	70.00	283673.22	8030.00	29.60
Mining	31.43	200.00	49.51	50.00	37087.36	2400.00	15.50
Recreation	42.18	25.00	12.58	12.50	237.80	14.90	10.20
Fallow	22.86	1.00	21.23	0.50	17.97	6.39	2.09
Others	35.20	25.00	565.46	12.50	56403.80	318.00	177.00

[a] Values less than 0.01.

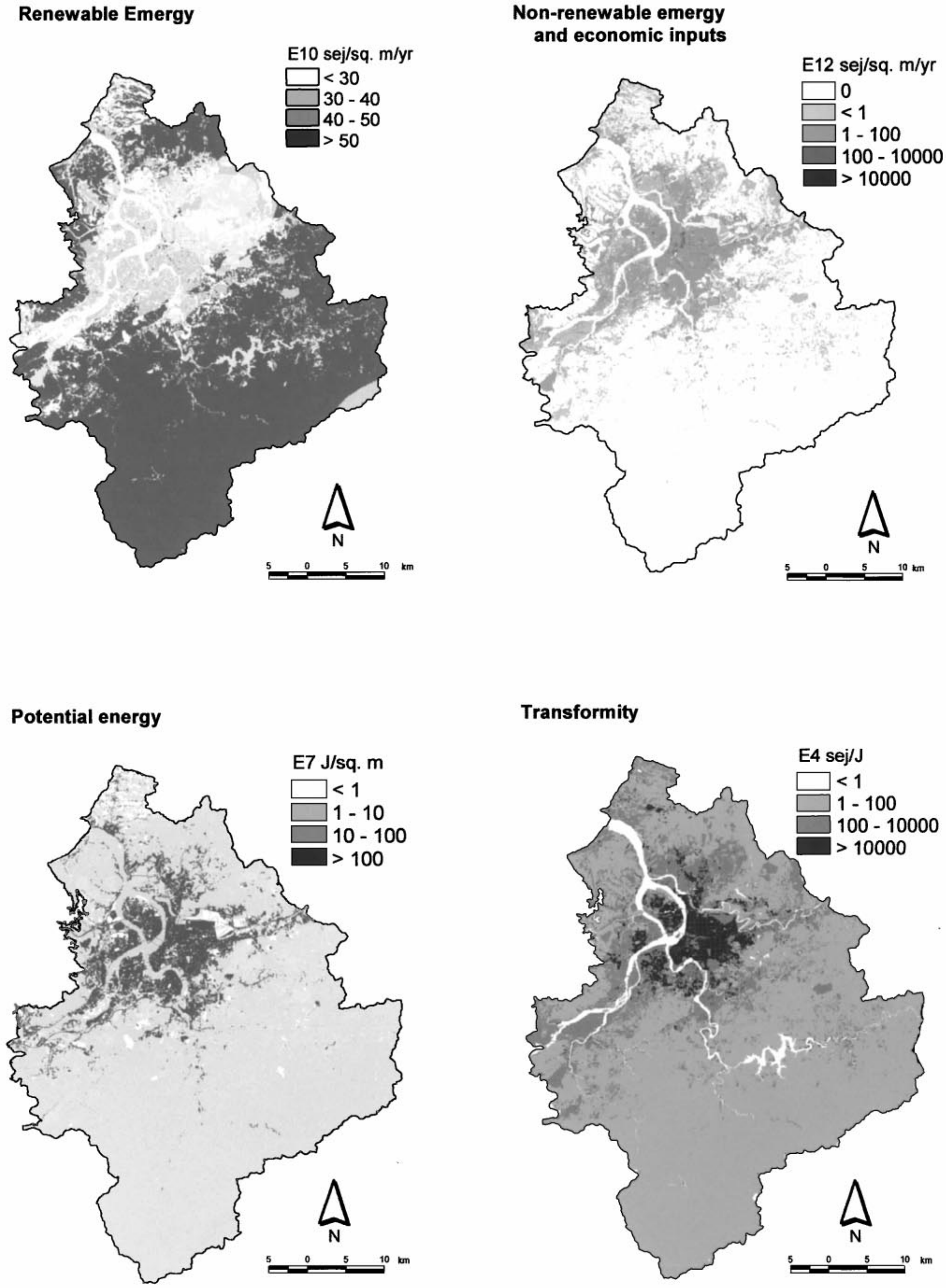


Fig. 3. Energy flows and transformity of Taipei metropolitan region.

sumption conditions (Odum et al., 1995). Huang (1998b) developed a system model, which includes five consecutive zones to represent Taipei metropolis. Over a span of time each zone within the urban landscape of Taipei metropolis was evolved as a result of energy convergence.

The rationale supporting the concept that an urban landscape can be divided into zones with different

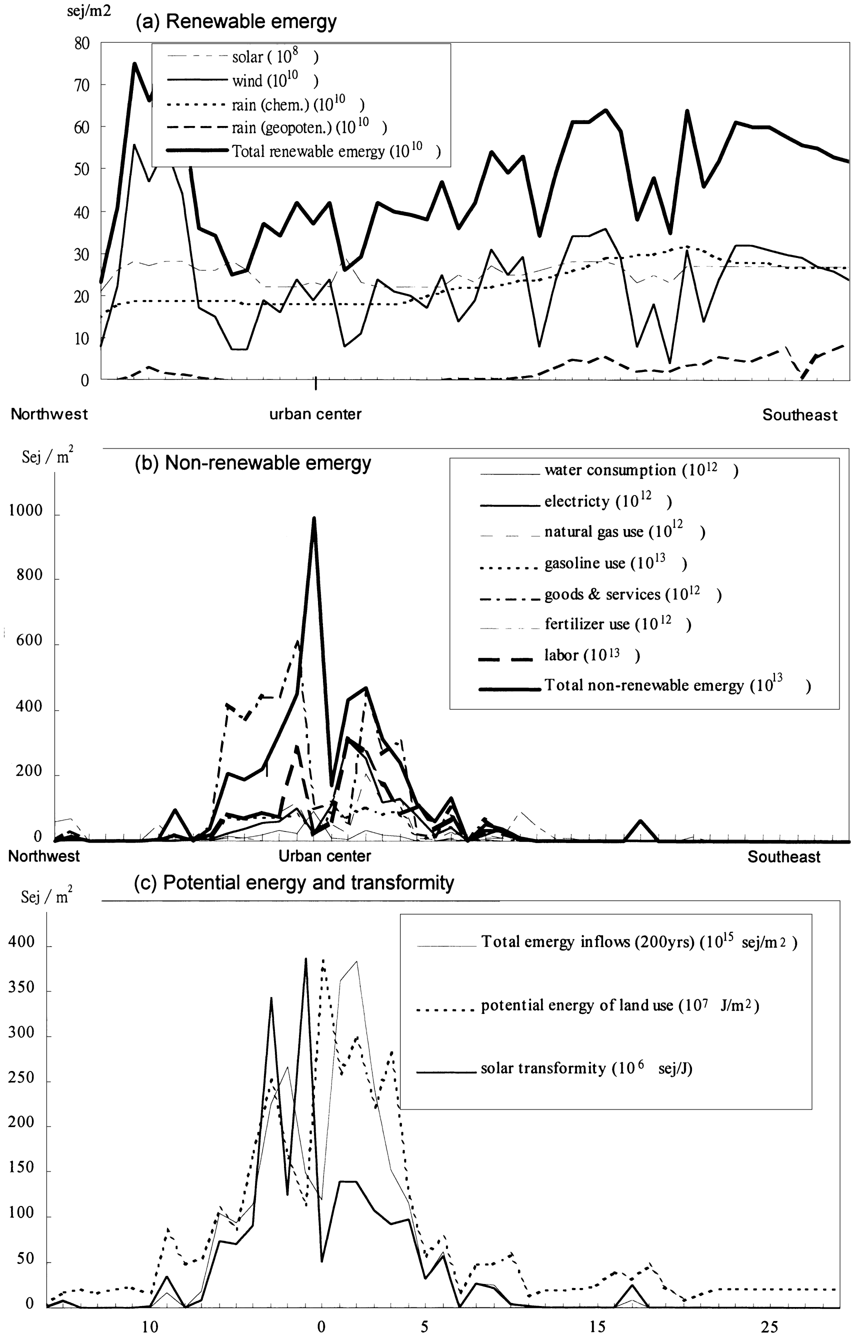


Fig. 4. Northwest–southeast transact of emergy flows and transformity of Taipei metropolitan region.

hierarchies is that each locality receives different types and quantity of energy to produce its services for the system as a whole. Fig. 5 displays a simplified diagram of the energy system of an administrative district, which includes the types of energy inflows and outflows to be used as variables for classification. In all, the variables of location, altitude, renewable emergy flows (solar, rain, wind, etc.), nonrenewable emergy flows (petroleum, natural gas, fertilizer, electricity, etc.), economic inputs (labor, services, goods, etc.), and outputs (urban productivity, wastes, etc.), were chosen for classifying the 1178 administrative districts in order to show the energetic characteristics of the Taipei metropolitan region. Thereafter, factor analysis was initially utilized to reduce the dimension of the problem. A reduction of the data represented by the 19 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 2. These factors collectively explain 74.3% of the variation in the original data set. Factor I is most strongly associated with the variables related to wastewater and solid waste generation, water consumption, natural gas use, and inputs of goods and services, and can be interpreted as a resource consumption factor. Factor II summarizes variables related to renewable emergy flows, such as rain, solar energy, and altitude. Factor III is predominantly related to electricity, fertilizer, labor, gasoline, and petroleum products, and therefore, is a factor of economic activity. Factor IV is a factor of urbanization because of the positive correlation with urban productivity, and negative correlation with wind, distance to urban core, and migration.

The estimated factor scores of the four extracted factors were used as input for grouping the administrative districts. The non-hierarchical *K*-means clustering technique was chosen to maximize the within-cluster sum of squares as well as to maximize the between-cluster sum of squares. Euclidian distance was used to compute dissimilarities since all variables for each administrative district were expressed on a continuous numerical scale. The overall mean square ratio was used to decide which partition is most acceptable (Howard and Howard, 1981). Table 3 indicates that the large value of R for $K = 6$ followed by the small value for $K = 7$ suggests that six groups would be a plausible grouping number which would minimize the within-cluster sum of squares. The final step of the classification process involved the application of discriminant analysis to the factor scores of administrative districts within clusters, which provided a test for the validity of the initial groupings. The classification functions were established to reclassify the administrative districts.

Taipei metropolitan region can be clustered into six homogeneous zones of ecological energetics. Further, in order to reveal the energetic characteristics of each group and investigate their energy hierarchy, emergy indices were calculated for each group and transformities were used to rank their hierarchical order. These groups can also be related by the mean values of the original variables (Table 4). Fig. 6 displays the spatial distribution of the six energetic zones. Since they are characterized by high transformities, the three urban districts, which are located in the central portion of Taipei Basin, represent the metropolitan region's highest levels within the urban ecological economic system of hierarchy. All three zones of urban districts have high empower densities and emergy investment ratios, indicating their low self-sufficiency of emergy and high reliance on economic inputs. Specifically, the zone of mixed-use urban core is dominated by highest urban productivity. The zone of high density urban residential district has high consumption of natural gas and municipal water supply, and generation of wastes; its inflow of goods and services are also the highest among all the six zones. The zone of service and manufacturing district is characterized by higher densities in the use of electricity and gasoline consumption, indicating that it is a commercial and service-oriented industry. The zone of agricultural district has got the highest fertilizer emergy use, and the densities in the use of electricity, domestic water consumption, and generations of wastes decreased considerably as compared to the three urban districts. Since being relatively close to the urban areas, the emergy density of consumption of transportation fuel in agricultural district, estimated by traffic volume, is higher than its surrounding zones.

The zone of newly developed suburban district is located between the agricultural district and the natural area. While residential area dominates the land use activity of the newly developed suburban district; its urban productivity, utility use, imported goods and services, and total empower density are only higher

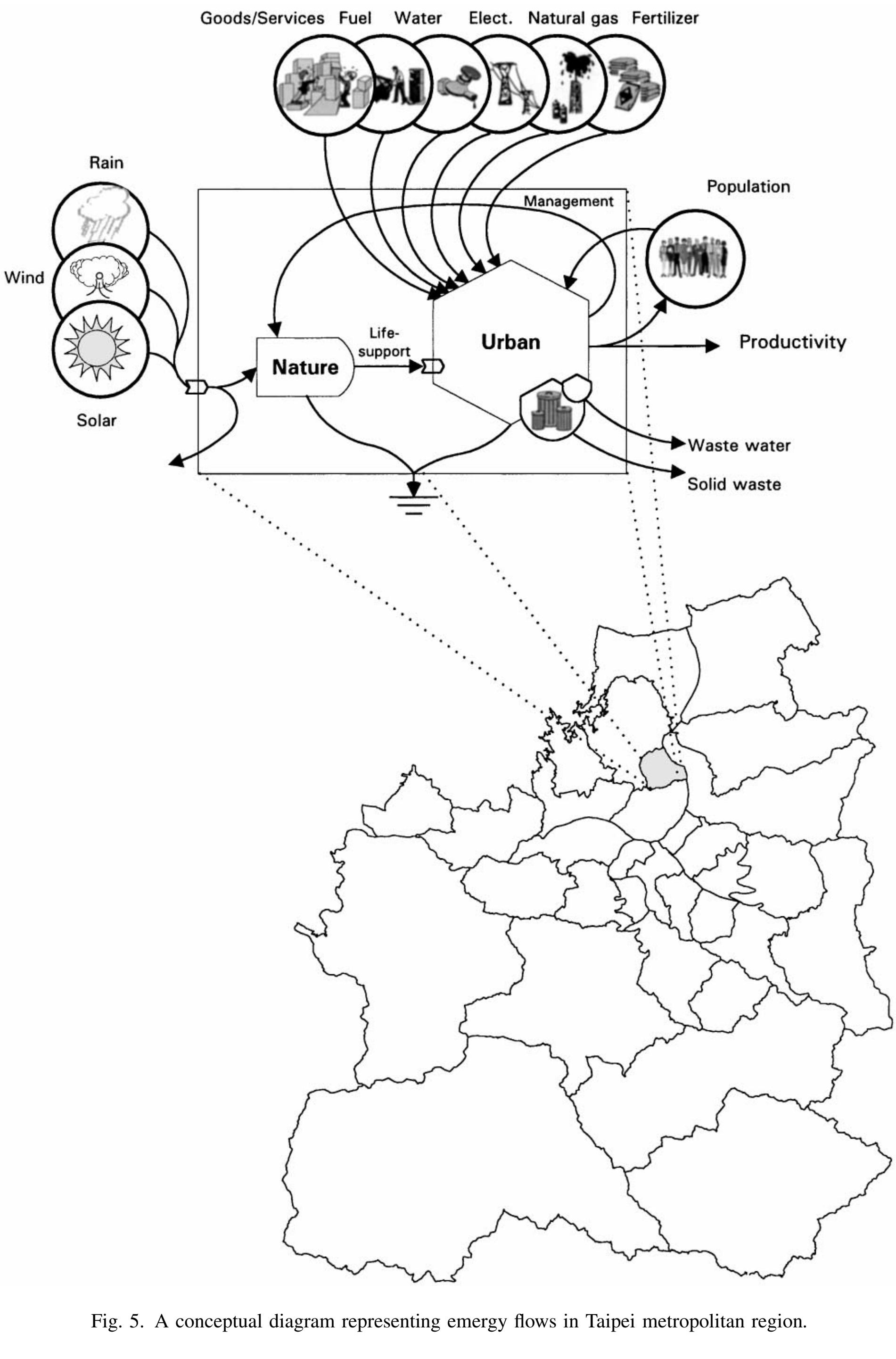


Fig. 5. A conceptual diagram representing emergy flows in Taipei metropolitan region.

Table 2
Related factor loading matrix in the 1178 districts of Taipei metropolitan region for urban energetic classification[a]

Variable	Factor[b]			
	I (resource consumption)	II (renewable emergy)	III (economic activity)	IV (urbanization)
Wastewater generation	**0.91652**	−0.16856	0.17832	0.18631
Water consumption	**0.89869**	−0.13771	0.19850	0.25080
Solid waste generation	**0.88696**	−0.13329	0.21726	0.23300
Natural gas	**0.87291**	−0.11400	0.24394	0.26239
Imported goods	**0.86542**	−0.22325	0.17237	–[c]
Imported services	**0.70441**	−0.19914	0.21114	0.31481
Rain (geopotential)	−0.15987	**0.89187**	–	−0.23443
Altitude	−0.18349	**0.87340**	−0.11153	−0.28240
Rain (chemical)	−0.15502	**0.75622**	−0.23298	–
Solar energy	−0.41001	**0.50244**	−0.48499	−0.40906
Labor input	0.15678	−0.21012	**0.68203**	–
Electricity use	0.29094	−0.27476	**0.62090**	0.32907
Fertilizer use	−0.26593	–	**−0.60732**	−0.14664
Gasoline use	0.34154	−0.32671	**0.60553**	0.47697
Imported petroleum products	−0.19427	−0.40895	**0.57795**	–
Urban productivity	0.12564	−0.17778	0.14820	**0.71743**
Wind energy	–	0.45155	0.36363	**−0.63538**
Distance to urban core	−0.29137	0.40577	−0.39272	**−0.59417**
Population migration	−0.16470	−0.22161	−0.39927	**−0.58343**
Eigen value	8.89845	2.53802	1.55319	1.12539
Total variance (%)	46.8	13.4	8.2	5.9
Cumulative total variance (%)	46.8	60.2	68.4	74.3

[a] The units for all variables, except altitude and distance to urban core, are in empower density (sej/m^2).
[b] The values in bold correspond to the variables which are strongly associated with the respective factors.
[c] Values less than 0.1.

Table 3
Total sum of squares and overall mean square ratio for different partitions of 1178 administrative districts

Number of groups (K)	Total sum of squares (TSS)	Overall mean square ratio (R)[a]
2	3896.1	–
3	3130.2	278.74
4	2547.6	268.72
5	2321.4	114.40
6[b]	1728.7	402.15
7[c]	1620.7	78.13
8	1492.9	100.98
9	1370.1	104.91
10	1356.0	12.09

[a] The overall mean square ratio $R = [(\mathrm{TSS}_K/\mathrm{TSS}_{K+1}) - 1] \times (M - K - 1)$, where M is the number of objects.
[b] $K = 6$ has the highest value of R.
[c] $K = 7$ has the lowest value of R.

than the natural area. The natural area is the zone of the lowest energy hierarchy, which has the highest flow of renewable emergy and generates very low emergy of wastes; where the total empower density is also the lowest. The zone of natural area comprises of 60% of the Taipei metropolitan region, which can be considered as Taipei metropolis' life support environment. Although the total energy flow and land areas are less in the urban districts, the areal concentration of empower and transformity increases to the urban centers.

5. Discussion

On the basis of the types and amount of energy flow, the 1178 administrative districts of Taipei metropolitan region were classified into six homogenous zones. In order to simulate the evolution of urban zonation of

Table 4
Summary of emergy flows and emergy indices of six energy zone of Taipei metropolitan region

Emergy	Zone					
	Mixed-use urban core	High density urban residential	Service and manufacturing urban district	Agricultural district	Newly developed suburban district	Natural area
Indices						
Transformity (10^7 sej/J)	**16.43**[a]	11.75	7.69	2.74	2.17	0.53
Total empower density (10^{13} sej/m^2 per year)	51.57	**94.32**	26.21	7.44	5.11	0.19
Emergy investment ratio (10^1)[b]	149.27	**254.36**	76.81	23.92	14.88	0.36
Per capita emergy used (10^{16} sej/pop)	**3.84**	1.43	0.65	2.29	0.98	2.07
Per capita fuel emergy used (10^{16} sej/pop)	**1.01**	0.31	0.13	0.47	0.17	0.22
Ratio of waste to renewable emergy	427.56	**648.00**	151.87	51.59	30.31	0.51
Fraction of renewable emergy used	0.07	0.03	0.06	0.47	0.57	**0.94**
Ratio of waste to total emergy used	**0.28**	0.25	0.17	0.19	0.07	0.01
Fraction of fuel emergy used	**0.25**	0.21	0.19	0.07	0.06	0.007
Fraction of electricity emergy used	0.13	0.08	**0.33**	0.08	0.09	0.004
Flows (sej/m^2 per year)						
Solar (10^9)	2.23	2.21	2.24	2.53	2.58	**2.74**
Wind (10^{11})	1.64	1.94	1.72	1.24	2.80	**3.02**
Rain (chemical) (10^{11})	1.98	1.89	1.87	2.08	2.00	**2.73**
Rain (geopotential) (10^5)	7.09	6.36	5.99	70.74	85.85	**693.89**
Electricity use (10^{13})	6.93	7.34	**8.49**	1.43	1.17	0.04
Natural gas use (10^{13})	12.49	**19.69**	4.34	1.27	0.72	0.01
Water consumption(10^{12})	20.22	**32.68**	7.87	3.00	1.73	0.10
Gasoline use (10^{12})	10.35	10.09	**10.74**	2.71	1.97	1.11
Wastewater generation (10^{12})	17.33	**28.71**	5.87	2.13	1.34	0.24
Solid waste generation (10^{13})	13.12	**21.21**	4.58	1.41	0.92	0.02
Urban productivity (10^{15})	**4.47**	3.35	3.69	3.27	1.53	1.10
Fertilizer use (10^7)	0.99	1.45	1.29	**17.87**	10.26	9.08
Imported goods (10^{14})	2.39	**5.44**	0.97	0.35	0.24	0.005
Imported services (10^{13})	5.15	**8.52**	1.74	0.67	0.42	0.01

[a] Values in bold represent the highest value among the six zones.
[b] Emergy investment ratio: (emergy use of nonrenewable sources + emergy inputs from economic system)/emergy inflows of renewable energy.

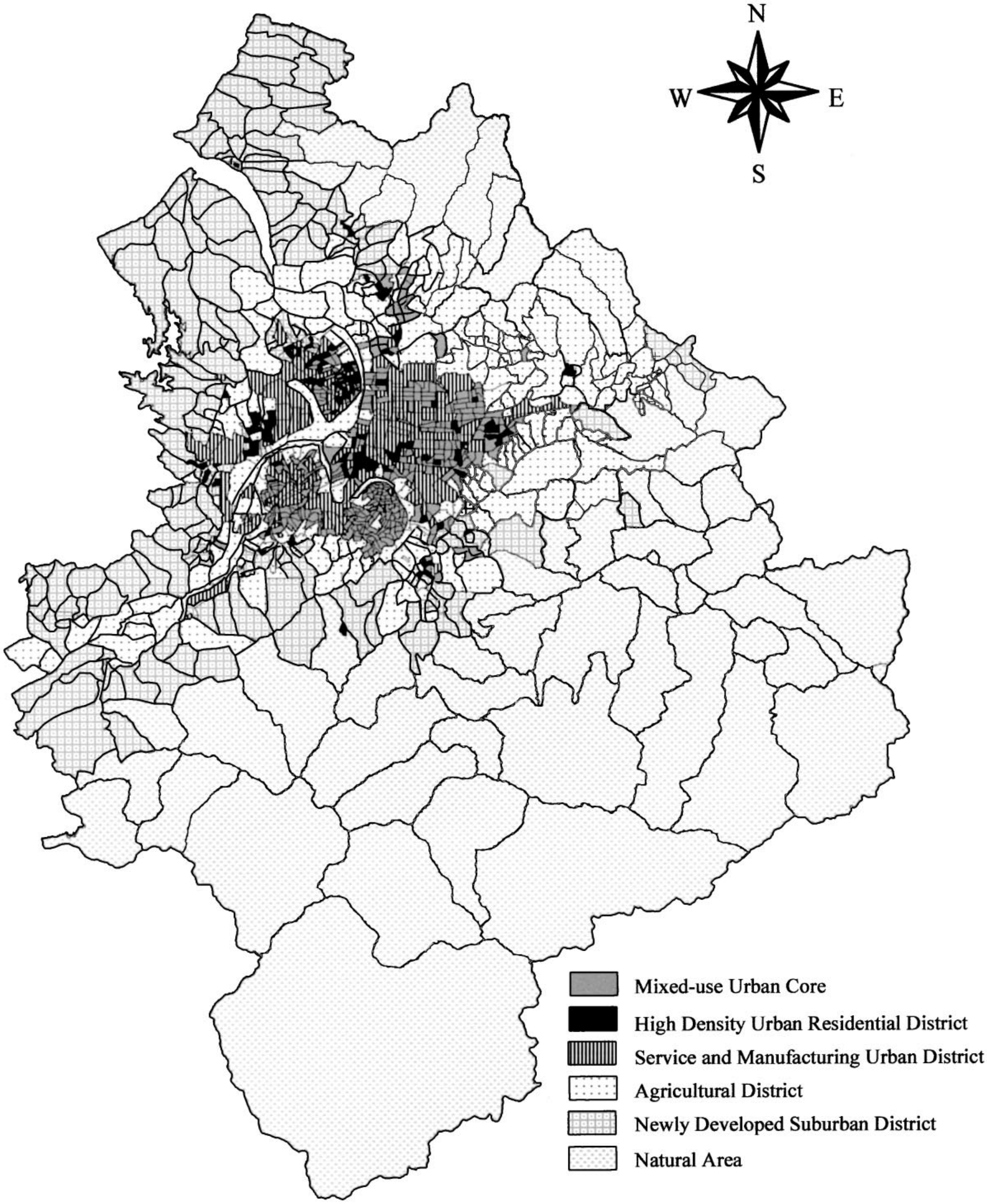


Fig. 6. Geographic distribution of urban energetic zones of Taipei metropolitan region.

Taipei, Huang (1998b) developed a system model comprising of five consecutive zones (natural, agricultural, residential, town and industrial, and urban center); where the residential zone is likely to be outcompeted by the neighboring zone and become a town district. In this research, although there are six zones derived as a result of the taxonomic classification. However, judging by their energetic characteristics and spatial distribution, the three zones of urban district can be regarded as a single urban center. The results of the arrangement and properties of Taipei's zonal system is similar to Huang's previous findings. The distribution of these six energetic zones reveal the spatial hierarchy of energy convergence from natural to rural and than to the urban center. The zones with higher energy hierarchy are located in the center, and the hierarchies of zones decrease as they move away from the center (see Fig. 6). But, the hierarchical arrangement of these energetic zones do not quite follow the successive order of land use hierarchies (see Fig. 1 and Table 1). The agricultural district has higher transformity than the newly developed suburban district, and instead of locating between the zones of natural area and the newly developed suburban district as proposed by Huang (1998b), the zone of agricultural district is located on the outskirts of urban districts (see Fig. 6). This is as a result of the consequence of rapid urban sprawl in the Taipei metropolitan region during the past decades; wherein a significant amount of natural areas were developed and converted to suburban use. It is too often found that economic development diverts high quality energy without regard to the role these energies have in the landscape as a whole; with a consequence of developing natural area such as soil erosion, water pollution, etc. at the cost of society. The areas, whose neighboring zones have much higher energy hierarchy, are likely to be affected by it, since the natural area, located adjacent to the newly developed suburban district (see Fig. 6), would either be affected by urban activities from its neighboring districts or by development in the future. Moreover, the higher investment ratio (239.2) of agricultural zone, as compared to that of newly developed suburban district (148.8), depicts its heavy reliance on inputs from human economy for production; the result of this high emergy investment ratio is the loosing in the economic competitiveness and an inefficient use of the land. It is contemplated that the area currently classified as agricultural district is under severe development pressure. The direction for planning and managing the areas which do not follow the arrangement of energy hierarchy is of vital importance to the sustainability of the metropolitan region. A good policy for planning a landscape is to arrange, and to converge and diverge materials in complete cycles. Moreover, urban and regional planning, especially the national urban policy, must be directed to channel urbanization along the evolutionary paths that are as little environmentally exploitative as possible. Expenditures on diverging and dispersing wastes back to the rural systems are as important as those spend on to bring products into the centers of an economy.

An understanding of the interactions between urbanization and natural environment is of prerequisite importance for an ecologically sensitive and economically rational accommodation of urbanization. The rationale behind all land classification schemes is the concept of functional integration of individual environmental components within defined spatial limits, thereby producing discrete identifiable units of land. The purpose of developing land classification systems for planning and management of land is to divide the landscape, or to cluster land units, into various-sized ecosystem units that have significance for development of resources and planning for conservation of the environment. Land use activity on zones with mismatch hierarchy (e.g. industry in natural area, agriculture in urban center, etc.) requires higher energy investment to maintain its socioeconomic viability. The investment ratio is high in the urban cores and low in the rural lower energy areas outside. An economic activity in an area cannot compete well if its investment ratio is higher than the surrounding area. The maps of investment ratio can be of use to find appropriate areas for economic activities of different intensity. A policy for locating future developments can be aided by maps with concentration of emergy use and transformity so that these beneficial areas can be found.

6. Conclusion

Viewing urbanization as a change in the source and amount of energy flow from rural to urban core provides a workable conceptual link between urbanization and natural environment. Using a multivariate technique, this paper represents a continuing effort of Huang (1998a,b) to delineate different energetic zones to study the spatial hierarchy of Taipei metropolis. As a result, different energy structures, and subsequently, different types and amount of energy flow tend to be associated with different stages and intensities of urbanization. The growth and form of Taipei City and its vicinity are not without influence from the surrounding life support systems. Using GIS to display energy flows in a spatial context, the distribution of the six energetic zones can reveal the spatial energetic hierarchy within Taipei metropolis. It is quite clear that zones of urban districts, situated along Tamsui River in Taipei Basin, which are also in the central of Taipei metropolitan region, are energy converging center in the Taipei metropolis. Moreover, as a spatially hierarchical center of population, resource consumption and waste generation, Taipei City exerts a profound influence on local, and regional environmental life support system. The city processes reach out to the surrounding zones for interactions to mutually benefit. The use of fuels, minerals, electric power and goods and services can only generate their best contribution to the wealth of the city when they interact with the environmental resources so as to be mutually amplifying. However, due to its high urban productivity, the city of Taipei can present tremendous opportunities to reinforce the production potential of the surrounding life support systems to achieve an ecologically sustainable development.

Using emergy concept, this paper concludes that energy hierarchy also explains the land use hierarchies and their arrangement in the landscape with urban area in the center. Further details regarding the calculation and distribution of energy flows in Taipei metropolis can be found in Huang (1997). We envisage the continuing application of emergy synthesis for studying urban ecological economic system in several directions:

1. How does the pattern of energetic zones change spatially during the evolutionary process of the city? This will require either the collection of data over a period of time, or integration of the GIS with dynamic simulation to study the evolving pattern or urban zonation.
2. How do the neighboring zones with different energy hierarchies interact energetically? In what relations: competing, mutually cooperative, or symbiotic? And what is the outcome of their interaction? This would involve field work and surveys on the micro level to trace energy flows and transformation between different zones and to monitor the changes in the human activities.
3. How to establish a criteria for determining the optimal or plausible distribution of areas for each energetic zones? What is the relationship between emergy indices and urban sustainability? Such works would require comparison between different metropolis and an investigation on the status and role of the metropolis from a regional, national, or even a global perspective.

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