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Socioeconomic metabolism in Taiwan: Emergy synthesis versus material flow analysis

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Abstract

The concept of socioeconomic metabolism can be traced back to 19th century and can provide a useful framework for both natural and social scientists to study the interrelations between human societies and their natural environments. Many studies on socioeconomic metabolism incorporated material flow analysis, but there are still many unresolved methodological issues such as its units, aggregation techniques, and omitted energy flows. The importance of the relationships between land use and socioeconomic metabolism has also been raised recently. In order to combine material flows and energy flows, this paper incorporates emergy synthesis to overview the socioeconomic metabolism of Taiwan during 1981–2001. Due to the lack of natural resources, the extraction of domestic non-renewable materials has decreased since 1980s and have to be supplemented by import. The requirements of imported energy flows has increased substantially with industrial development. Difference between results from material flow analysis and emergy synthesis is also discussed. It is found that material flow analysis alone could not identify the essential fact of Taiwan's increasing dependence on energy use. Furthermore, the qualitative characteristics of materials flows are also neglected. The analysis of the relations between land use and socioeconomic metabolism indicates that the changes of land use affect the socioeconomic metabolism in Taiwan. However, due to the lack of information, whether the change of socioeconomic metabolism has triggered land use change still need further investigation.

Keywords: Emergy synthesis; Material flow analysis; Land use change; Socioeconomic metabolism; Taiwan

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1. Introduction

Environmental awareness in the 1960s triggered an interest in studying society's metabolism with a new perspective (Ayers and Kneese, 1969; Boyden et al., 1981; Meadows et al., 1972; Odum, 1971; Wolman, 1965), one which cut across the boundaries between the natural sciences and social sciences. Ever since the publish of the Brundtland Report, the notion of sustainable development has emerged as a key means to stimulate dialogue across the natural social sciences. Metabolism is a concept adopted from biology, which refers to the physiological processes within a living organism that describes the energy flow connected to the conversion of matter for reproduction. Extending this concept to the social sciences, metabolism can be seen as a main feature in the analysis of human interactions with the natural environment.

The organization of flows of materials and energy between human societies and their natural environments should be concerned with sustaining the metabolism of the societies. Socioeconomic metabolism (alternatively termed societal metabolism or industrial metabolism) is currently one of the research area of the human dimensions of global change project of the International Human Dimension Programme (IHDP). The concept of socioeconomic metabolism can be traced back to 19th century as the biophysical perspective of ecological economics (see Martinez-Alier, 1987). It has also been frequently examined in the field of human ecology (e.g. Boyden et al., 1981; Rappaport, 1971; Wolman, 1965). The notion of socioeconomic metabolism can provide a useful conceptual framework for both natural and social scientists to study the interrelations between human societies and their natural environments. Social scientists can study socioeconomic dynamics as a consequence of the changing patterns of material and energy flows while the natural scientists can analyze the effects of these flows to natural processes (Haberl, 2001).

After review of research on the application of metabolism to the social sciences from 1860 to 1998, Fischer-Kowalski (1998) noted that consensus for a theoretically stringent approach is emerging. Currently, most of the work on socioeconomic metabolism focus on the accounting of the inputs and outputs of materials flows of a specified society. The establishment of material flow accounts (MFA) as regularly collected statistical information has been implemented in some countries. For example, industrial countries such as Austria, Japan, Germany, and Sweden have established material flow accounts (Eurostat, 2001). MFA regards the socioeconomic system as the core of analysis and emphasizes inputs and outputs of this system. Specifically, these accounts look at the amount of materials extracted from nature, used and transformed in one way or another within society, and returned into natural system as wastes or emissions. However, there are still many unresolved issues using material flow analysis, such as its units, aggregation techniques, and omitted energy flows.

The synthesis of socioeconomic material and energy flows would greatly enhance our understanding of the driving forces of our ecological economic system. Monetary valuation of ecosystem services and natural capital may be useful to demonstrate their economic value but is insufficient to measure the intrinsic worth of the life support function of ecosystem (Costanza et al., 1997). Energy flows are not only one of the most important unifying concepts in ecosystem development (Odum, 1988). They are also the only common measure that connects ecosystems and economic systems (Hall et al., 1986). Consequently, using energetic flows to study socioeconomic metabolism seems to be necessary to provide a common value basis for evaluating the materials flows in the socioeconomic system.

The sustainability problems of societies may arise not only from their metabolism, but also from land use changes. Land use is the most important socioeconomic driver of ecosystem change. Although land cover is modified by societies to enhance various types of productivities, it also accelerates the consumption of energy and results in the increase of indirect material flows such as erosion. How does our society use the land and what is the relationship between socioeconomic metabolism and land uses?

In this paper, we begin by reviewing concepts of socioeconomic metabolism, discussing the methodological issues of material flow analysis, and introducing concepts of emergy for synthesizing socioeconomic metabolism (Section 2). Our analysis of Taiwan's socioeconomic metabolism begins with three basic questions. First, how did the socioeconomic metabolism of Taiwan change during the past decades? Second, what's the problem of analyzing materials flows without consideration of energy flows, or, can ecological energetic analysis be used to analyze socioeconomic metabolism? Third, is land use change and changes in socioeconomic metabolism related? Section 3 presents the results of applying emergy concept to synthesize Taiwan socioeconomic metabolism and compares the difference between the results of material flow analysis and emergy synthesis. Section 4 discussed the differences between results of material flow analysis and emergy synthesis, the role of material flows and energy flows on socioeconomic metabolism, and the relationships between land use transformation and change on socioeconomic metabolism. Conclusions of this research are given in Section 5.

2. Concepts and methods

2.1. Socioeconomic metabolism and material flow analysis

According to Fischer-Kowalski and Haberl (1997), society's relationship with nature can be characterized into two aspects: societal metabolism and colonization. Societal metabolism is the mode in which societies organize the exchange of matter and energy with their natural environment. After thorough review of research on the application of metabolism to social science, Fischer-Kowalski (1998) inquired into the scientific traditions of social theory, cultural anthropology, and social geography in their application of the biological concept of metabolism to social systems as a material and energetic process within the economy and society. In order to sustain the processes of life, an organism obtains raw materials from the environment for its metabolic reactions, converting these materials into the building blocks of proteins and other compounds necessary for life. In biological terms, the metabolism includes two processes. Through a series of chemical processes, *catabolism* breaks down the food and its derivatives to yield new building blocks and energy. *Anabolism* then produces and builds living cells. Humans, like any other animals, maintain a metabolic level for survival and reproduction, drawing energy from complex organic compounds and converting most of these compounds through respiration. A society must sustain a metabolic level that is at least equal to total metabolism of entire human population. However, if there is a surplus, this will rarely be processed through human bodies.

Therefore, the concept of societal metabolism needs to be expanded beyond the collective anabolic and catabolic activities of individual humans to encompass materials and energetic flows and their transformations associated with living organisms (Fischer-Kowalski, 1998).

Fischer-Kowalski (1998) also raised the question of to what degree do material and energetic processes that fit under the label "metabolism" provide a useful understanding of the interrelation of society and nature. From system ecology's point of view, human societies should be viewed as subsystems of the biosphere. The biosphere is closed materially yet an open system with respect to energy flows. Human societies should be considered open systems with regard to both material and energy flows. In addition to maintaining the throughput of energy and matter for survival, socioeconomic metabolism differs from biological metabolism by organizing the resource throughput purposively and even changing natural system intentionally to gain better access to nature's supply of resources (Schandl and Schulz, 2002). One of the ideas behind socioeconomic metabolism analysis is that flows of materials are required and used to build up the biophysical structures of society. These can be divided into three categories: (1) human bodies; (2) artifacts such as buildings machines and tools; (3) domestic animals and livestock (Haberl, 2001). Some studies, e.g. Stahmer et al. (1997), also include agricultural crops in the society's biophysical structure (see Haberl, 2001). Through the application of energy, human societies extract raw materials from their natural environment and convert them into goods and services and finally into wastes. Human societies transform the resource inputs in an economic process to provide material goods for domestic demand. The materials stayed within the socioeconomic system and become the society's economic assets, including, for example, buildings, roads, machines, etc. Other materials are released into the environment as by-products in the form of wastes.

The materialist analytical framework can provide the necessary main features for an economic-ecological analysis of the interaction between human society and natural environment. For example, the important aspects of the transitions from hunter-gatherers to agrarian societies, and to current industrial society can be studied by tracing their socioeconomic metabolisms (Haberl et al., 2004). The materials flow of socioeconomic metabolism can be measured in terms of the rate of mass input from the natural environment into the human society. However, the material relationship between man and his environment cannot simply be viewed from its input–output processes, namely the extracting and processing of materials (Fischer-Kowalski and Haberl, 1997). In order to sustain the socioeconomic metabolism, the materials from natural system are transformed into economic assets to maximize their usefulness for human societies.

Early material flow analyses focused on identifying material flows in socioeconomic metabolism and the national level seems to have been the most productive application of socioeconomic metabolism analysis. In order to provide a more convenient tool for summarizing the sustainability of countries, the complex process of material flow analysis has been compiled and aggregated to material flow accounts (MFA). MFA are patterned after traditional accounting practices by providing an aggregate overview by weight of annual material inputs and outputs of an economy, including inputs from a country's natural environment, outputs to the environment, and trade accounting for imports and exports in terms of physical quantities traded. Wernick and Ausubel (1995) utilized MFA to evaluate socioeconomic metabolism. WRI (2000) adopted the structure and estimated "the weight of nations", which considered the loss during the process of extracting, production, and transit. Eurostat (2001) established a standard procedure of MFA, which used similar structure to WRI. In the framework of MFA, the "total material requirement" includes indirect flows of "unused extraction", namely the flows that do not enter the economy under consideration but are mobilized to produce the goods and services consumed. The analysis of "unused extraction" also play an important role in assessing society's impact on the natural environment. The accounting of indirect flows of unused domestic extraction (e.g. by-products from agricultural harvest) and recalculating the trade-related hidden flows of semi-manufactured and final products into their raw material equivalents still presents methodological difficulties (Schandl and Schulz, 2002).

2.2. Methodological issues of material flow analysis

2.2.1. Omitted energy flows

Preferential treatments on material were given to previous studies on socioeconomic MFA rather than on energy flows. Material flow accounting has been developed and standardized internationally as a national approach for analyzing socioeconomic metabolism of material flows (Eurostat, 2001). Haberl (2001) proposed that both energetic and material aspects of societal metabolism must be taken into account to broaden the scope of the metabolism approach and to fully exploit the potential of this method in the context of sustainable development. Haberl (2001) further argued that the analysis of energy flows is essential in achieving a complete understanding of socioeconomic metabolism because the maintenance of a continuous flow of materials is possible only when a continuous inflow of energy is available as driving force to power the transport and transformation of material throughput of a society.

Ostwald, a Nobel prize chemist, was the first to study socioeconomic system from an energy viewpoint. Odum (1971, 1983) using general systems theory develops the principle of autocatalytic designs where consumers could feedback small amount of energy to power more energy from its supporting systems. Adams (1988) also considered energy to be a trigger of human civilization. Giampietro et al. (1992) assessed the amount of power used to alter ecosystems during the process of socioeconomic metabolism. Energy flow of the socioeconomic system can be viewed in the same way as an ecologist would describe the energy flow in an ecosystem. The accounting system for the socioeconomic metabolism should also consider flows of energy which drive the material flows.

Most current research on socioeconomic metabolism ignores energy flow because of the difficulty of comparing materials and energy with the same units. Energy flows are omitted in the standard evaluation of MFA, and indeed this is its most contentious issue. Haberl (2001) proposed an energy flow accounting (EFA) method which is consistent with MFA to analyze energy flows that enter and leave a national economy. The MEFA framework developed by Haberl et al. (2004) analyzes important interactions between social and natural systems by tracing socioeconomic materials and energy flows and by assessing changes in ecosystems (e.g. land use) related to these flows. However, the addition of energy flows for socioeconomic metabolism should go beyond the accounting of energy flows and further incorporate energetic principles to assess the relative contribution of various material and energy flows.

2.2.2. *System boundary*

Socioeconomic metabolism defines the biophysical structures of a society in a way that is compatible with compartment models of systems ecology (Haberl, 2001). The study of socioeconomic metabolism should be confined to systemic perspective rather than linear processes of material flows. A system boundary must be drawn between the socioeconomic system and its environment to identify the relevant materials and energy flows for the metabolism of the society. This boundary can be between nations as accounted for in national MFA or between a city and its surroundings as in urban metabolism.

An MFA of socioeconomic metabolism focuses on the flows between economy and environment, but the interactions between elements are ignored. The relations between a socioeconomic system and its natural environment are very complex and difficult to separate. MFA attempts to simplify the flows as inputs and outputs through the socioeconomic system boundary. However, this omits countless flows and interactions within and between the natural environment and socioeconomic system.

2.2.3. *Units of weight versus energy*

MFA is seen as an instrument for aggregating various materials flows into a few strategic indicators such as total material flows of a society. MFA can be broken down into "substance flow analysis" that deals with chemically defined substances, but Fischer-Kowalski and Huttler (1998) proposed that "bulk materials flows" (e.g. wood, construction materials, air, etc.) should be emphasized on socioeconomic metabolism in a more comprehensive way.

As it is currently applied, material flow analysis uses mass (e.g., tons) to measure the weights of material inflows and outflows of societal metabolism. However, the qualitative usefulness of different materials to socioeconomic system is not comparable using this measure. The aggregate of different materials flows using a common metric to measure the metabolism of human societies is similar to adding the vegetables and meats consumed by human body—the results can be misleading. It is necessary to aggregate material flows for an overview of a socioeconomic system, but during the process of aggregation, the qualitative characteristics of materials are most certainly ignored. The quantity of material flows are known, but the identity of materials is lost, with a subsequently dramatic effect on MFA policy indicators, i.e., heavy materials of some kind will drive the direction of policy.

2.3. *Land use and socioeconomic metabolism*

There are close relations between land use change and socioeconomic metabolism. Land use change is one of the major socioeconomic driving forces of environmental change. Land use and land cover change (LUCC) is a joint project of International Human Dimension Programme (IHDP) and International Geosphere-Biosphere Programme (IGBP) to study and document temporal and geographic dynamics of land use and land cover. The relationship between land use change and socioeconomic metabolism can be looked upon at different levels. One may choose to look at the global geo-biosphere, or one may choose to look at a nation, at regional unit, or finally at some functional unit such as an industrial district or farm.

In addition to natural factors such as climate, slope, hydrology, and soils, land use patterns are determined by social and economic driving forces. To sustain their metabolism, human societies deliberately transform matters from natural systems in ways that tend to maximize their usefulness for human purposes. Krausmann (2001) presented an empirical analysis of changes in land use, agricultural productivity, and socioeconomic metabolism of biomass as a result of industrial modernization in Austria during the 19th and 20th centuries. The study shows an intimate relation between patterns of socioeconomic metabolism and land use. Changes in the energetic basis of socioeconomic metabolism change the significance and function of biomass use for human society. Schandl and Schulz (2002) use land use data to strengthen the accuracy of the resource data as well as to add information on changing land use patterns. Krausmann et al. (2003) further analyzed relations between changes in land use and land cover and socioeconomic metabolism of Austria to analyze to what extend changes in socioeconomic metabolism trigger changes in land use, or changes in land use lead to transformations of socioeconomic metabolism. The analysis shows that industrialization in Austria changes the function of land use for society's metabolism.

2.4. Emergy synthesis

One of the basic ideas of material flow accounting is the attempt to reach a full balance in integrating inputs and outputs. But, not all MFA studies have taken this input–output rule seriously (Schandl and Schulz, 2002). Although material balancing can check data gaps in materials flows and provide a useful policy tool to integrate resource input and waste strategies, the conversion of materials into useful products within the socioeconomic process is often ignored. In addition, the aggregate of material flows using mass also neglects the relative contributive values of materials with different qualitative contents. Furthermore, human societies are dependent on material and energy from natural system, but they have emergent properties that cannot be fully understood by analyzing the biophysical structures sustaining them (Haberl et al., 2004). What is needed is a methodological framework that integrates inputs of outputs of material flows within the context of intra-economic relations.

Although energy balances are commonly used in economics to trace energy flows through the economy, it is often limited to commercial energy and omits the renewable energies which drive the life support function of the ecosystem. Energetic socioeconomic metabolism can consider societal energy flows in the broader context of ecological energetic and thereby treat socioeconomic components as part of the ecological economic system. From an ecological energetic point of view, all flows of materials can be regarded as energy flows. Relying only on statistical data, one will significantly underestimate the relevant amounts of resource throughput. Ecological energetic analysis allows one to trace energy flows through a society in considerable detail. The analysis of energetic socioeconomic metabolism can draw upon the available data although it should also consider those energy flows not accounted for in energy balances.

In order to evaluate the contributory value of different material flows to the ecological economic system, a new accounting system is required that can assess biophysical value of resources to economic system. Based on the general system principles and laws of thermodynamics, Odum (1971, 1983) designs a set of energy circuit symbols (Fig. 1) for describing the interactions of ecosystem components via energetic flows. Odum has formulated a unifying theory of system ecology of values (Odum, 1971, 1988, 1996) and introduced two terminologies—emergy and transformity. Emergy is defined as *all the available energy that*

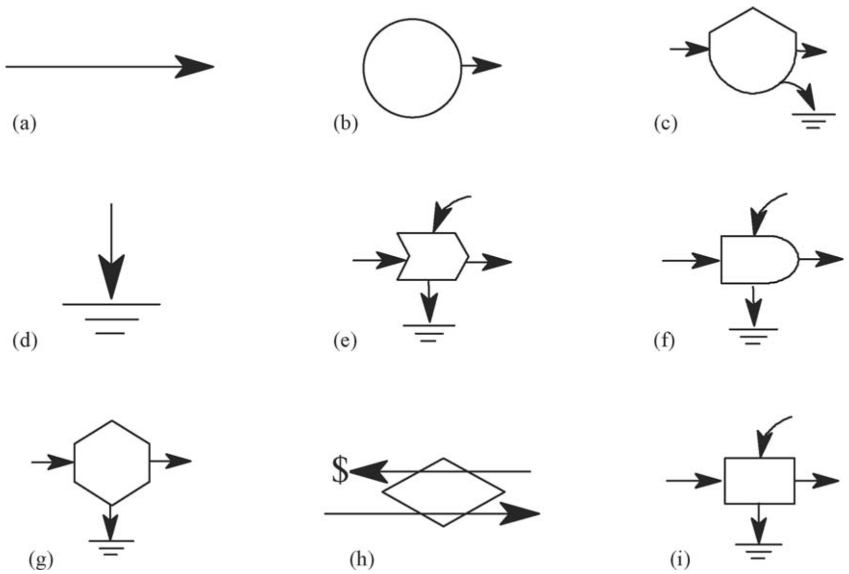

Fig. 1. Energy circuit symbols: (a) energy circuit; (b) source; (c) tank; (d) heat sink; (e) interaction; (f) producer; (g) consumer; (h) transaction; (i) box.

was used in the work of making a product in units of one type of energy; transformity is *the emergy of one type required to make a unit of energy of another type* (Odum, 1996). It is suggested that an energy system diagram using the energy symbols in Fig. 1 should be drawn to provide an overview of the study area and its subject of study, and to identify the sources of flows and major processes. An emergy synthesis table can then be developed to quantify the emergy content or mass of the identified flows. For the purpose of taking into account the varied qualities of energy content inherent in the material and energy flows of the socioeconomic system, the energy content (e.g. joule) or mass of a flow can be multiplied by its solar transformity to obtain its solar emergy in solar emergy joules (sej) (Fig. 2). These values then substitute for the units of mass in the material flow analysis.

Item	Raw Data	Solar Transformity (sej/unit)	Solar Emergy	Em$
⋮				
Rain	$6.56*10^{17}$ J	15,444 J/sej	$101.33*10^{20}$ sej	$2,571.99*10^{6}$ $
⋮				
Limestone	$1.13*10^{13}$ g	$1*10^{9}$ g/sej	$113.31*10^{20}$ sej	$2,867*10^{6}$ $
⋮				

Fig. 2. Emergy synthesis table.

Emergy indices such as ratio of imported material flows to total emergy used or per capita total material use can be calculated for policy evaluation. Further details on the concept and procedure of emergy synthesis can be found in Huang and Odum (1991), Odum (1996), and Brown and Ulgiati (2004). Huang and Hsu (2001) incorporated concept of emergy to evaluate material flows of Taipei's urban construction. Although the volume of the sand and gravel used was found to be ten times higher than that of cement, the emergy value of cement used dominated the total emergy flows of material used for urban construction. This was due to the higher transformity of cement. Past research on socioeconomic metabolism has placed emphasis on the weight of resource flows and ignores the varied qualities of material flows. We now turn to the incorporation of emergy synthesis with material flow analysis to overview the socioeconomic metabolism from viewpoint of ecological energetics. Differences between results from material flow analysis and emergy synthesis will also be discussed.

3. Emergy synthesis of Taiwan's socioeconomic metabolism: 1981–2001

In order to incorporate emergy synthesis to socioeconomic metabolism, we confine ourselves to overall materials flow analyses on the national level. The overall material metabolism of a nation is embedded in its geo-biosphere and therefore is considered a subsystem of the ecological economic system. The case study used in this paper is Taiwan, a highly industrialized country with high population density (area 36,000 km^2, current population 23 million, population density 638 people/km^2). The Taiwan landscape is dominated by the steep mountainous region in the central portion of the island. Most of the people reside on the western coastal plain where agricultural activities and major cities are located. Land use data for Taiwan were aggregated to four classes as shown in Table 1. Urban area consists of built-up areas, transportation, urban parks, etc. The agricultural area includes rice paddy fields, vegetable crop lands, orchards, aquaculture ponds, irrigation facilities, etc. Miscellaneous areas are dikes and drainage ditches. During the past 20 years, the urban area in Taiwan has increased from $1.57 \times 10^4\,km^2$ in 1981 to $2.26 \times 10^4\,km^2$ in 2001. This expansion was due to the conversion of rice paddy field to built area. The natural area has decreased due to their conversion into agricultural land for vegetable crops and orchards. Consequently, agricultural land decreased in 1980s and then increased in the 1990s.

Table 1
Taiwan's land use statistics: 1981–2001

	Urban area (km^2)	Agricultural area (km^2)	Natural area (km^2)	Miscellaneous[a] (km^2)	Total (km^2)
1981	1569.60	9851.52	24590.94	26.62	36038.68
1986	1796.67	9627.91	24544.41	37.12	36006.12
1991	2000.49	9783.69	24172.16	62.02	36018.36
1996	2105.65	9787.95	24059.77	73.44	36026.81
2001	2263.26	9819.66	23865.51	77.48	36025.91

[a] Dike and ditch.

3.1. *Taiwan's material flow analysis*

Study of changes in socioeconomic metabolism might not occur as gradual development but rather as from regime to another, for example, from agricultural to industrial society, which brought about changes in the energy sources and resource use patterns. Due to the lack of data available to study the change of socioeconomic metabolism of Taiwan from agricultural society to the current post-industrial stage, we incorporate in this study the stage when Taiwan undergone rapid economic growth to the current stage of stabilized economy.

Basically, the empirical study of the metabolism of a socioeconomic system begins with an analysis of societal inputs and outputs of materials and energy flows. On the national scale, energy and materials flows can be divided into: (1) domestic sources, both renewable and non-renewable; (2) imports; (3) exports; (4) wastes. This distinction is relevant for analyzing the biophysical process of a socioeconomic system.

The main flow of domestic renewable materials into Taiwan's economy is represented by agricultural products (Fig. 3). Sugarcane represents 50.2% of the biomass input to Taiwan's socioeconomic system in 1981, but by 2001 production had decreased to less than 20% due to shrinking foreign market. Rice production also decreased from 2.4×10^6 t in 1981 to 1.4×10^6 t in 2001. Due to government regulation for soil and water conservation, timber harvests decreased to only 3.4×10^4 t. Vegetables, fruits, livestock, and aquaculture production all increased during the past decade. The overall domestic renewable materials flow has been decreased during the past 20 years. The extraction of non-renewable resources, however, has increased (e.g. sand and gravel, marble) during the 1981–2001 due to the construction activities associated with rapid economic growth (Fig. 4).

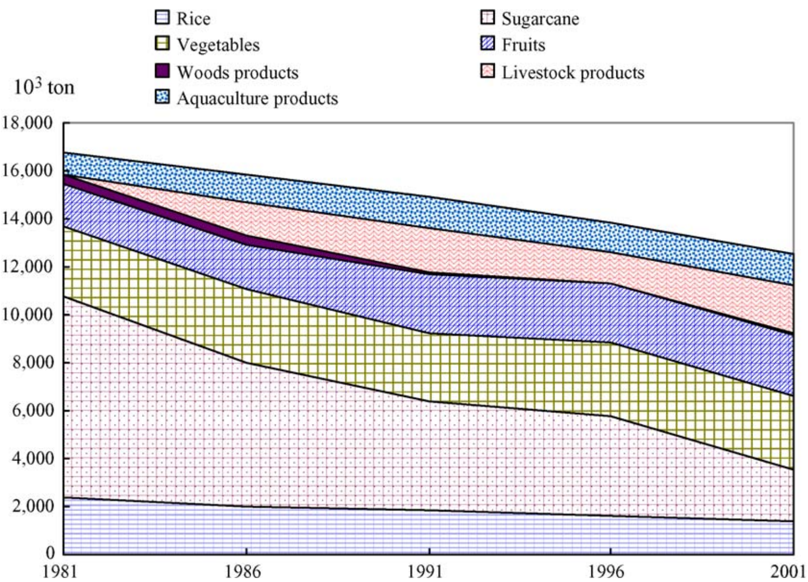

Fig. 3. Domestic extraction of biomass in Taiwan's economy: 1981–2001.

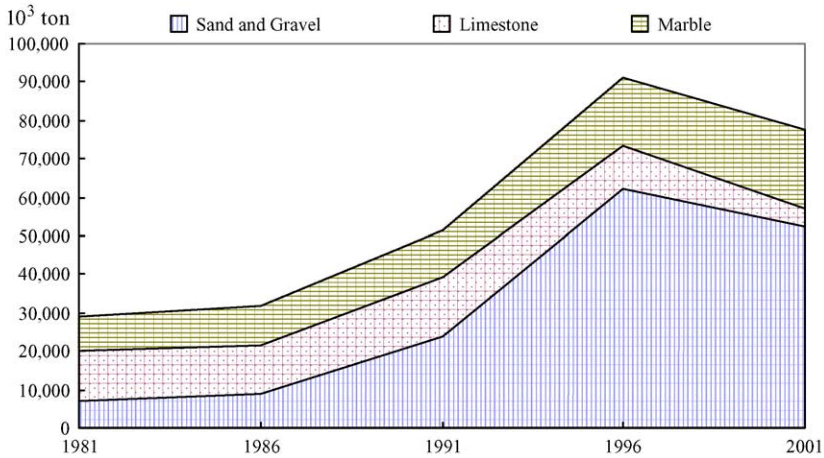

Fig. 4. Domestic extraction of construction materials in Taiwan's economy: 1981–2001.

Due to its limited natural resources, Taiwan has to import the energy and raw materials it needs for industrial manufacturing and urban activities. Among all the imported items, fossil fuels represent the major imported flows during the past 20 years (Fig. 5). Imported coal has increased from 5.2×10^6 t in 1981 to 9.7×10^7 t by 2001. Imported oil has also increase from 2.4×10^5 to 5.7×10^6 t during the past 20 years. Taiwan's rapid economic

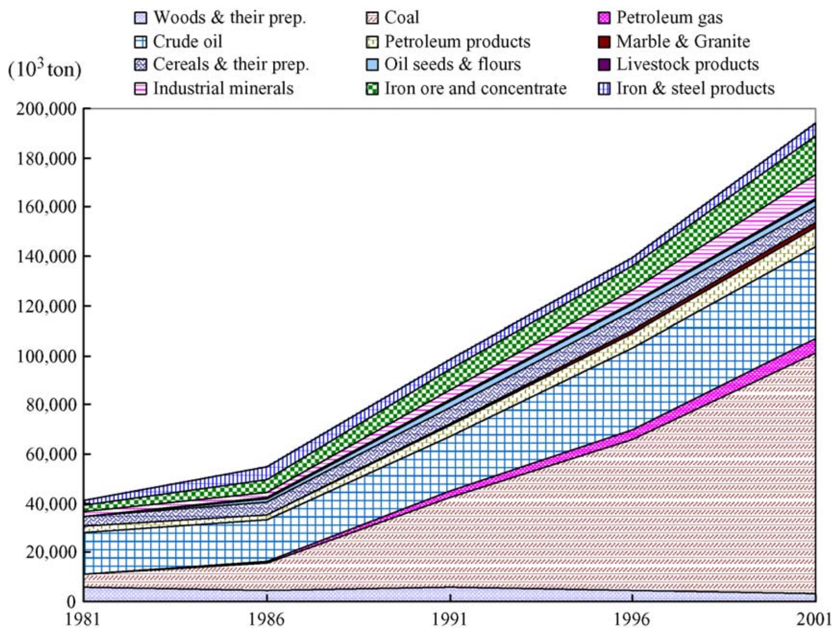

Fig. 5. Import of materials and energy in Taiwan's economy in tons: 1981–2001.

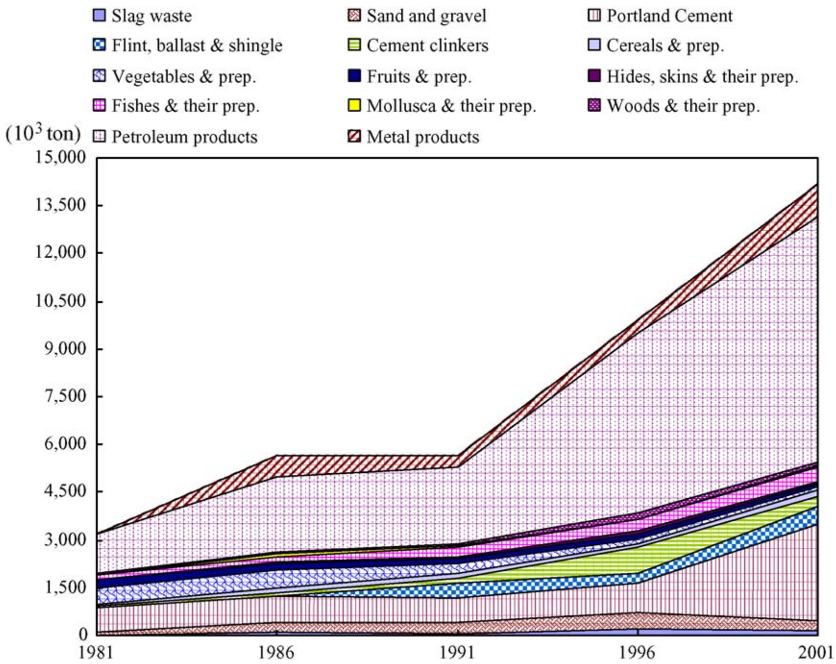

Fig. 6. Export from Taiwan's economy: 1981–2001.

growth has been fueled by its exports. The export of cement, petroleum products and iron products have increased significantly, but the export of vegetables and fruits has decreased during the past 20 years (Fig. 6).

3.2. Emergy synthesis of Taiwan's socioeconomic metabolism

From the perspective of systems ecology, the biophysical structures of a socioeconomic system can be regarded as compartments of storages drawing material or energetic inputs from their environment or supporting compartments, building up internal stocks and discharging outputs to support compartments at higher hierarchical level or across boundaries into the environment. For an analysis of energetic socioeconomic metabolism, we identify major materials flows and placing them within the context of an ecological economic system, using energy system diagrams, and including the energy flows necessary to drive materials flows. Once the physical compartments of the socioeconomic system are defined, it becomes possible to distinguish between stocks and flows of energy and materials.

Taiwan's socioeconomic system is represented by means of energy systems symbols in Fig. 7. The diagram explicitly incorporates the socioeconomic system, natural land, agricultural land, renewable resources, imports and exports. The resource elements in the system are selected on the basis of a 95% threshold (by weight) from each material category in Taiwan's material flow analysis (Lin, 2000), and a 95% threshold (in emergy units) from Taiwan's emergy synthesis table in Huang and Odum (1991) to identify important items

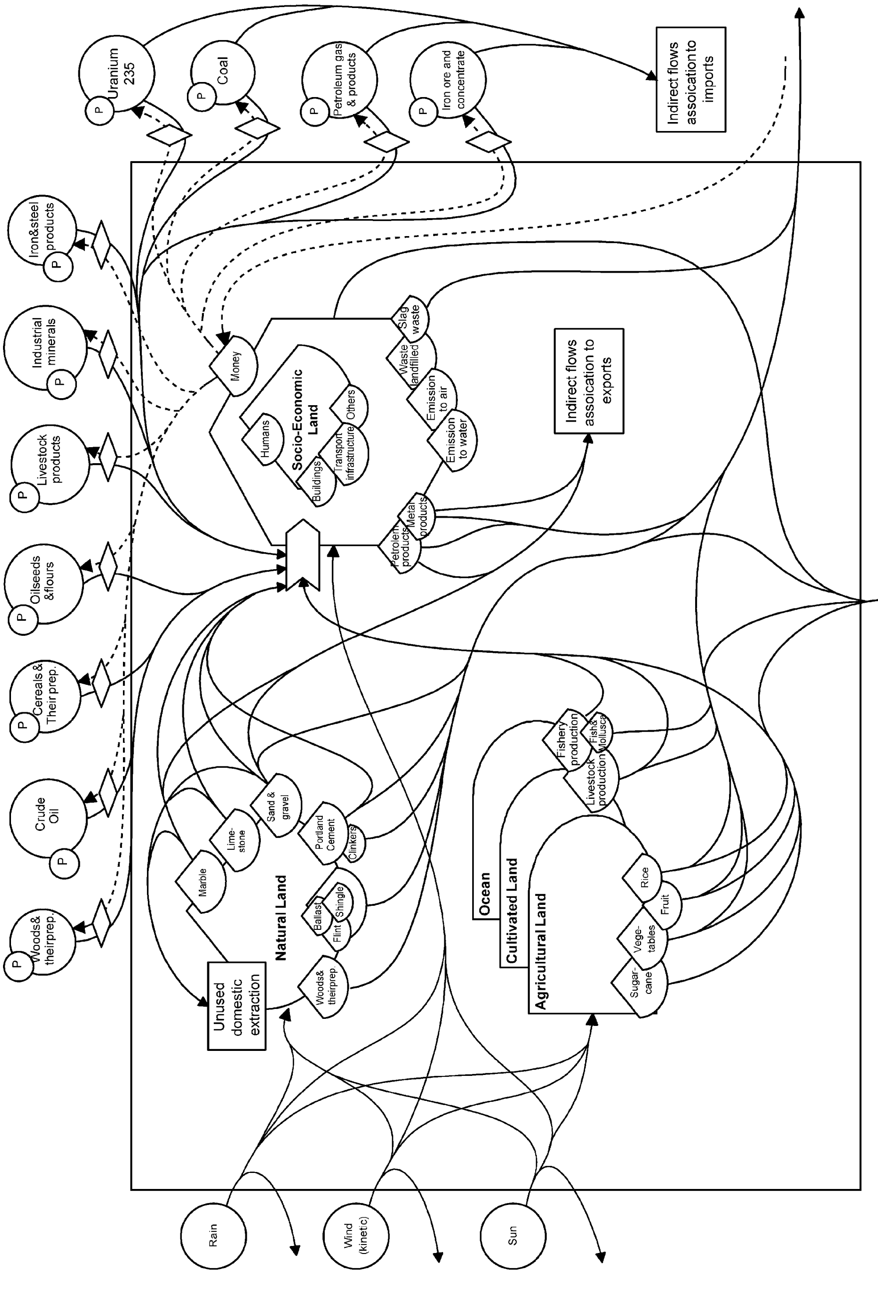

Fig. 7. Energy diagram of Taiwan’s socioeconomic system.

Table 2
Emergy synthesis of Taiwan's socioeconomic metabolism: 1981–2001

Resources Item	Solar emergy ($\times 10^{20}$ sej)				
	1981	1986	1991	1996	2001
Inflows of renewable energy					
1. Sun (J)	2.72	2.72	2.72	2.72	2.72
2. Wind (kinetic) (J)	13.73	13.73	13.73	13.73	13.73
3. Typhoons (J)	21.34	17.07	12.80	12.80	21.34
4. Rain (geopotential) (J)	54.26	51.18	43.05	57.27	50.26
5. Rain (chemical) (J)	96.02	90.56	76.18	101.33	88.93
6. Tide (J)	0.64	0.64	0.64	0.64	0.64
7. Geologic uplift (J)	33.84	33.84	33.84	33.84	33.84
Renewable resources utilization					
8. Wood consumption (J)	2.31	2.19	0.36	0.22	0.19
9. Hydroelectricity (J)	273.43	424.22	314.60	517.28	507.02
10. Water used (J)	45.78	65.74	77.94	89.24	93.17
11. Sugarcane (g)	32.09	22.87	17.28	15.96	8.31
12. Rice (g)	104.50	86.85	80.02	69.40	61.44
13. Fruits (g)	106.44	113.94	152.19	151.45	159.21
14. Vegetables (g)	369.17	394.11	360.85	385.48	383.62
15. Livestock production (g)	0.00	327.11	442.66	313.68	476.47
16. Fishery production (g)	649.02	779.24	937.32	882.50	937.50
Non-renewable resources from within Taiwan					
17. Sand and gravel (g)	0.00	0.00	0.01	0.02	0.02
18. Electricity used (J)	214.71	308.54	464.19	637.23	816.52
19. Nuclear electricity (J)	58.33	148.13	194.24	208.32	212.12
20. Marble (g)	4.73	5.64	6.51	9.63	11.26
21. Limestone (g)	132.21	124.54	153.47	113.31	49.01
22. Erosion (T)	147.74	147.74	147.74	147.74	147.74
Import					
23. Uranium 235 (J)	0.00	0.00	211.71	98.45	71.41
24. Coal (J)	60.49	128.32	426.14	717.59	1136.08
25. Petroleum gas (J)	5.77	13.86	60.00	82.28	137.38
26. Crude oil (J)	418.66	418.17	545.68	813.67	916.41
27. Petroleum products (J)	62.83	48.56	139.68	183.10	228.16
28. Marble and granite (g)	0.00	0.03	0.31	0.72	1.16
29. Woods and their prep (g)	31.40	26.09	31.73	24.97	19.38
30. Iron ore and concentrate (g)	14.60	32.42	51.02	60.95	94.21
31. Industrial minerals (g)	14.37	14.46	34.98	42.33	79.19
32. Iron and steel products (g)	40.57	89.62	67.03	59.48	94.63
33. Cereals and their prep. (g)	312.46	357.93	481.74	527.69	473.04
34. Oil seeds and flours (g)	0.00	131.18	157.25	195.72	177.81
35. Livestock products (g)	0.00	125.04	145.18	201.80	180.15
36. Goods and services ($)	476.19	598.91	1522.62	2437.97	2520.34
Export					
37. Sand and gravel (g)	0.00	0.00	0.00	0.00	0.00
38. Petroleum products (J)	36.32	70.96	72.95	168.64	230.62
39. Woods and their prep. (g)	0.24	0.29	0.26	1.01	0.65
40. Flint, ballast and shingle (g)	0.00	0.00	4.70	3.04	5.60
41. Fruits and prep. (g)	16.83	12.34	10.11	7.72	5.58

Table 2 (*Continued*)

Resources Item	Solar emergy ($\times 10^{20}$ sej)				
	1981	1986	1991	1996	2001
42. Cereals and prep. (g)	6.56	13.90	13.23	9.38	14.48
43. Vegetables and prep. (g)	60.43	70.21	34.83	19.24	10.77
44. Metal products (g)	10.71	182.95	94.91	122.84	288.43
45. Slag waste (g)	0.76	26.05	16.57	73.41	55.03
46. Portland cement (g)	245.31	277.92	262.10	320.06	1003.36
47. Cement clinkers (g)	16.66	28.80	40.46	261.42	98.17
48. Fishes and their prep. (g)	114.22	134.29	225.57	256.95	325.42
49. Mollusca and their prep. (g)	0.00	53.96	39.20	21.08	32.42
50. Hides, skins and their prep. (g)	3.99	37.55	54.73	143.94	118.02
51. Goods and services ($)	495.59	912.42	1683.59	2624.89	2835.56
Waste produced					
52. Waste water	27.47	39.44	46.77	53.55	55.90
53. Solid waste	270.63	386.88	549.88	661.81	551.07

of resource flows in Taiwan's ecological economic system. The circular symbols outside the boundary of Taiwan represent the materials and energy inflows to Taiwan's ecological economic system. The renewable energies of sun, wind, and rain are the main drivers for natural land and resource production area. In addition to domestic extraction of non-renewable sources and domestic resource flows from agricultural land, the socioeconomic system has to rely on imports of fossil fuels and materials from foreign countries. The exports of agricultural products and finished products help generate the money inflow to Taiwan's economy.

Based on the energy and material flows presented in Fig. 7, an emergy synthesis of Taiwan's socioeconomic metabolism from 1981 to 2001 is provided in Table 2. The use of the renewable resources of water and hydroelectricity has doubled during the past 20 years. Similar to the trend of material flows, the emergy flows of sugarcane and rice production have decreased while fruits, vegetables, and fishery production have increased since 1981. The emergy flow of fishery production is the highest biomass production. Non-renewable domestic extraction of marble and electricity use are also rising. Due to its low transformity, the emergy flow of sand and gravel is relatively low as compared to other non-renewable flows. Aside from goods and services, the imports of fossil fuels such as coal, petroleum, and crude oil, and mineral from foreign countries have increased significantly during the past 20 years. Among exports, the emergy flows of petroleum products, Portland cement and metal products have increased significantly.

For a macro-viewpoint of Taiwan's socioeconomic metabolism, Table 3 shows an aggregation of resource flows into material flows, energy flows, and eco-economic emergy flows, both in units of solar emergy and tons. Taiwan's socioeconomic system underwent a transition from post-agricultural labor intensive manufacturing industry to high-tech based industrial society and experienced rapid economic growth during the period 1981 to 2001. In Table 3, we can see that during this industrial transition, Taiwan's emergy flows of domestic renewable material (DMFr) such as rice, sugarcane, vegetables, fruits, etc. become stable. However, because Taiwan is an island, which is not rich in some natural resources,

Table 3
Aggregated resource flows of Taiwan's socioeconomic metabolism

Code	Description	Solar emergy ($\times 10^{20}$ sej)				
		1981	1986	1991	1996	2001
Material flows						
TMU	Total material use (DMF + IMF) = domestic material flows + imported material flows ($\times 10^9$ kg)	1813.88 (62.07)[a]	2633.27 (71.65)	3119.92 (98.25)	3055.31 (140.05)	3206.58 (135.67)
IMF	Imported material flows (TMFnr + IMFr) = imported non-renewable materials + imported renewable materials ($\times 10^9$ kg)	413.40 (16.40)	776.78 (24.22)	969.23 (32.13)	1113.65 (35.14)	1119.57 (45.62)
IMFnr	Imported non-renewable materials = marble and granite + industrial minerals + iron ore and concentrate + iron and steel products ($\times 10^9$ kg)	69.54 (6.38)	136.54 (12.15)	153.34 (16.86)	163.47 (19.67)	269.19 (32.27)
IMFr	Imported renewable materials = woods and their prep. + cereals and their prep. + oil seeds and flours + livestock products ($\times 10^9$ kg)	343.86 (10.03)	640.24 (12.07)	815.89 (15.27)	950.18 (15.47)	850.38 (13.36)
DMF	Domestic material flows (DMFnr + DMFr) = domestic non-renewable materials + domestic renewable materials ($\times 10^9$ kg)	1400.48 (45.67)	1856.49 (47.44)	2150.69 (66.13)	1941.66 (104.91)	2087.01 (90.05)
DMFnr	Domestic non-renewable materials = sand and gravel + limestone + marble ($\times 10^9$ kg)	136.94 (28.89)	130.18 (31.62)	159.99 (51.19)	122.96 (91.03)	60.29 (77.49)
DMFr	Domestic renewable materials = rice + sugarcane + vegetables + fruits + wood consumption + livestock production + fishery production ($\times 10^9$ kg)	1263.54 (16.77)	1726.30 (15.82)	1990.70 (14.93)	1818.69 (13.88)	2026.73 (12.56)

Table 3 (*Continued*)

Code	Description	Solar emergy ($\times 10^{20}$ sej)				
		1981	1986	1991	1996	2001
EMF	Exported material flows (EMFnr + EMFr) = exported non-renewable materials + exported renewable materials ($\times 10^9$ kg)	512.03 (3.20)	909.20 (5.63)	869.61 (5.64)	1408.73 (9.91)	2188.56 (14.17)
EMFnr	Exported non-renewable materials = slag waste + sand and gravel + Portland cement + flint, ballast and shingle + cement clinkers + petrolem products + metal products ($\times 10^9$ kg)	309.77 (2.15)	586.68 (4.33)	491.68 (4.56)	949.41 (8.83)	1681.22 (13.09)
EMFr	Exported renewable materials = cereals and prep. + vegetables and prep. + fruits and prep. + hides, skins and their prep. + fishes and their prep. + mollusca and their prep. + woods and their prep. ($\times 10^9$ kg)	202.26 (1.05)	322.52 (1.29)	377.92 (1.08)	459.32 (1.09)	507.34 (1.08)
TMF	Total material flows (TMU + EMF) = total material use + exported material flows ($\times 10^9$ kg)	2325.91 (65.27)	3542.47 (77.28)	3989.52 (103.89)	4464.03 (149.96)	5395.14 (149.84)
Energy flows						
TEU	Total energy use (DEI + IEF) = domestic energy inputs + imported energy	976.17	1272.47	1968.86	2722.67	3298.15
DEI	Domestic energy inputs = renewable resources + hydroelectricity + nuclear electricity	428.42	663.55	585.65	827.57	808.71
ELEC	Electricity used	214.71	572.35	508.83	725.60	719.13
IEF	Imported energy flows = uranium 235 + coal + petroleum gas + crude oil + petrolem products ($\times 10^9$ kg)	547.75 (24.71)	608.92 (30.36)	1383.21 (66.09)	1895.10 (104.45)	2489.44 (148.34)
EEF	Exported energy flows	0.00	0.00	0.00	0.00	0.00
TEF	Total energy flows (TEU + EEF) = total energy use + exported energy	976.17	1272.47	1968.86	2722.67	3298.15
Economic energy flows						
R	Renewable resources in Taiwan = rain (chemical) + tide	96.66	91.20	76.82	101.97	89.57

N	Non-renewable resources in Taiwan	614.13	848.09	816.20	996.08	926.98
	N0 primary resource = erosion − wood consumption	145.43	145.56	147.38	147.52	147.56
	N1 concentrated used resource = hydroelectricity + nuclear electricity + sand and gravel + limestone + marble	468.70	702.53	668.82	848.56	779.42
	N2 direct export = sand and gravel + flint, ballast and shingle	0.00	0.00	4.70	3.04	5.60
F	Imported fuels and minerals = uranium 235 + coal + petrolem gas + crude oil + petrolem products + industrial minerals + iron ore and concertrate + marble and granite + iron and steel products	617.29	745.46	1536.54	2058.57	2758.63
G	Imported goods = woods and their prep. + cereals and their prep. + oil seeds and flours + livestock products	343.86	640.24	815.89	950.18	850.38
U	Total emergy used = R + N0 + N1 + G + F + IMS	1728.37	2445.14	3523.44	4517.86	5022.55
IMS	Imported services	56.43	120.14	277.99	411.05	396.99
EXS	Exported services	47.92	123.19	175.23	329.27	402.73
W	Waste produced	298.10	426.33	596.64	715.35	606.97
Pop	Population	1.81×10^{7}	1.95×10^{7}	2.06×10^{7}	2.15×10^{7}	2.24×10^{7}
X	GDP (US$)	4.68×10^{10}	8.03×10^{10}	1.83×10^{11}	2.79×10^{11}	2.72×10^{11}
P2	Emergy/money (world) (sej/$)	1.98×10^{12}	1.98×10^{12}	1.98×10^{12}	1.98×10^{12}	1.98×10^{12}
P1	Emergy/money (Taiwan) = total emergy used/GDP (R + N0 + N1 + G + F + IMS)/GDP (sej/$)	3.69×10^{12}	3.04×10^{12}	1.93×10^{12}	1.62×10^{12}	1.85×10^{12}
Domestic resources use	R + N0 + N1	710.79	939.29	893.02	1098.06	1016.55
Imported goods and services	F + G + IMS	1017.58	1505.84	2630.43	3419.80	4006.00
Exported goods and services	EMF + EXS	559.95	1032.39	1044.84	1738.00	2591.29

[a] The numbers in parenthesis are in unit tons.

the emergy flows of domestic non-renewable materials (DMFnr) had decreased and had to be supplemented by imports of material flows (IMF) from 413.4×10^{20} sej in 1981 to 1119.57×10^{20} sej in 2001. Nevertheless, due to the requirements of the socioeconomic system, the consumption of imported energy (IEF) increased substantially with industrial development.

Total emergy used (U) follows the same trend as resources use. The emergy flows of total material use (TMU) in Taiwan, including DMFr, DMFnr, IMFr, IMFnr, on the other hand, stabilized indicating that the material use in Taiwan has not changed significantly from 1991 to 2001. The industrial society in Taiwan has become a service industry society

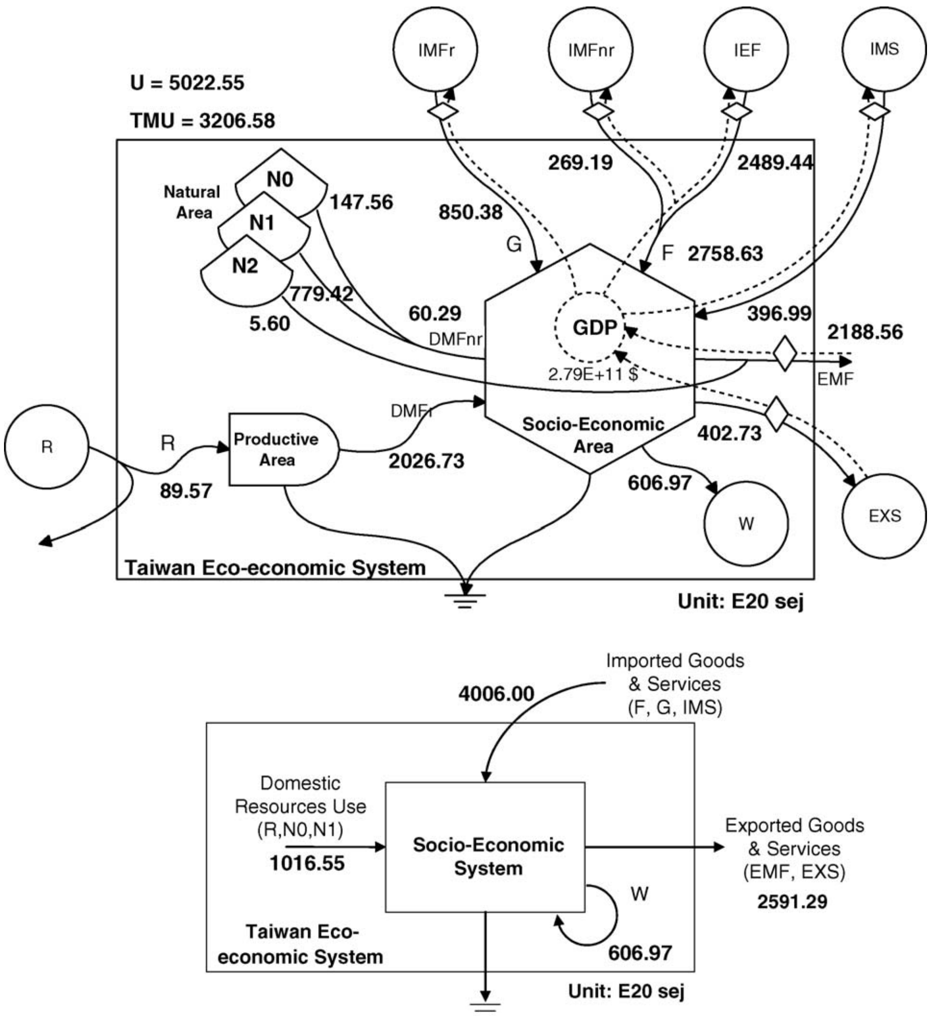

Fig. 8. Aggregate diagram of resource use in 2001.

that uses less materials. However, emergy flows of imported energy (IEF) have increased rapidly during the same period and have dominated as the major resource inflows to Taiwan's socioeconomic system. An aggregated diagram of resource use of Taiwan in 2001 is shown in Fig. 8. Taiwan's socioeconomic metabolism as conceived is driven by the imported goods and services, especially by the use of energy (IEF), which amounted to 2489.44×10^{20} sej in 2001. Energy inputs are the trigger of Taiwan's socioeconomic development. It appears that some kind of technical progress or industrial transformation has taken place in Taiwan in which the same amount of materials is being used to export more goods via increased energy inputs.

4. Discussion

This research compares the total flows of certain substances mobilized by a social system to the ecological system via emergy unit. After initial discussion of Taiwan's socioeconomic metabolism, some comparative analyses are made to argue our position regarding: (1) weight versus emergy; (2) material flows versus energy flows; (3) socioeconomic metabolism versus land use transformation.

4.1. Weight versus emergy

The use of weight, or mass, for evaluating socioeconomic metabolism while commonly used is often questioned in the analysis that we've undertaken. Characteristics of the materials are ignored during the process of material aggregation by weight. Although economic input–output analysis is highly related to MFA, an assessment of costs and benefits has seldom been incorporated into socioeconomic metabolism studies except for the measures such as material flows/GDP. The unit of weight used to measure materials flows does not take into consideration the relative worth of materials to the economy.

Table 4 summarizes the comparison of ranking of emergy value and weights of domestic renewable material flows. Sugarcane ranked number one during 1981–1996 in terms of weight, however, its emergy value is relatively low as compared to other agricultural products due to its low transformity, meaning its low contribution to the ecological economic system of Taiwan. Interestingly though, despite its lower mass, the higher emergy value of aquaculture yields play a much more important role in the economy than other products. Similar results were found for domestic non-renewable material flows (see Table 5). Ever since 1991, a significant amount (mass) of sand and gravel has been used for construction project, but due to its lower transformity, its emergy value is much lower than the extraction of limestone for cement.

4.2. Material flows versus energy consumption

The socioeconomic metabolic approach allows an examination of human societies and their natural environment through physical processes of materials and energy flows. Materials and energy are either imported or extracted from the indigenous environment, processed within socioeconomic system, accumulated as socioeconomic assets, and finally released

Table 4
Comparison of material flows using weights and emergy: renewable products

Domestic renewable flows	1981		1986		1991		1996		2001	
	Emergy ($\times10^{20}$ sej)	Rank	Emergy ($\times10^{20}$ sej)	Rank	Emergy ($\times10^{20}$ sej)	Rank	Emergy ($\times10^{20}$ sej)	Rank	Emergy ($\times10^{20}$ sej)	Rank
Aquaculture products	649.0	1	779.2	1	937.3	1	882.5	1	937.5	1
Vegetables	369.2	2	394.1	2	360.9	3	385.5	2	383.6	3
Fruits	106.4	3	113.9	4	152.2	4	151.4	4	159.2	4
Rice	104.5	4	86.8	5	80.0	5	69.4	5	61.4	5
Sugarcane	32.1	5	22.9	6	17.3	6	16.0	6	8.3	6
Woods products	2.3	6	2.2	7	0.4	7	0.2	7	0.2	7
Livestock products	0.0	7	327.1	3	442.7	2	313.7	3	476.5	2

Domestic renewable flows	1981		1986		1991		1996		2001	
	Weight ($\times10^3$ t)	Rank	Weight ($\times10^3$ t)	Rank	Weight ($\times10^3$ t)	Rank	Weight ($\times10^3$ t)	Rank	Weight ($\times10^3$ t)	Rank
Sugarcane	8422	1	6002	1	4536	1	4190	1	2180	3
Vegetables	2930	2	3128	2	2864	2	3059	2	3045	1
Rice	2375	3	1974	3	1819	5	1577	4	1396	5
Fruits	1717	4	1838	4	2455	3	2443	3	2568	2
Aquaculture products	912	5	1095	6	1317	6	1240	6	1317	6
Woods products	417	6	394	7	65	7	39	7	34	7
Livestock products	0	7	1386	5	1875	4	1329	5	2018	4

Table 5
Comparison of material flows using weights and emergy: construction materials

Domestic non-renewable flows	1981		1986		1991		1996		2001	
	Emergy ($\times 10^{20}$ sej)	Rank	Emergy ($\times 10^{20}$ sej)	Rank	Emergy ($\times 10^{20}$ sej)	Rank	Emergy ($\times 10^{20}$ sej)	Rank	Emergy ($\times 10^{20}$ sej)	Rank
Limestone	132.2	1	124.5	1	153.5	1	113.3	1	49.0	1
Marble	4.7	2	5.6	2	6.5	2	9.6	2	11.3	2
Sand and Gravel	0.0	3	0.0	3	0.0	3	0.0	3	0.0	3

Domestic non-renewable flows	1981		1986		1991		1996		2001	
	Weight ($\times 10^{3}$ t)	Rank	Weight ($\times 10^{3}$ t)	Rank	Weight ($\times 10^{3}$ t)	Rank	Weight ($\times 10^{3}$ t)	Rank	Weight ($\times 10^{3}$ t)	Rank
Limestone	13221	1	12454	1	15347	2	11331	3	4901	3
Marble	8599	2	10259	2	11837	3	17517	2	20475	2
Sand and gravel	7074	3	8908	3	24010	1	62186	1	52111	1

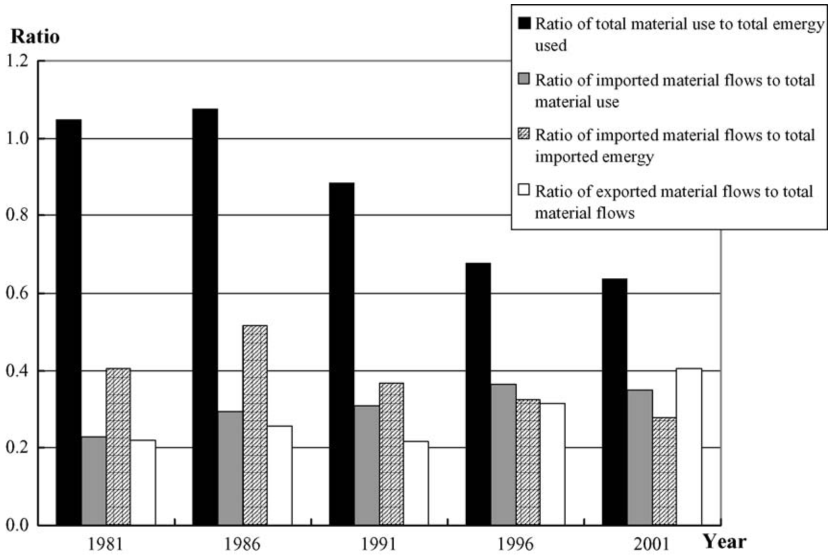

Fig. 9. Role of material flows in Taiwan's socioeconomic metabolism.

into the environment as wastes or exported to exchange foreign goods (Fischer-Kowalski and Haberl, 1997). In analyzing the metabolism of a socioeconomic system, one may look at the materials flows in terms of matter or energy or both; or one may select certain flows of chemical substances or materials. The study of the socioeconomic metabolism can be approached by studying the roles of certain input materials in the metabolic process. Alternatively, one can concentrate on output materials and try to investigate how the system generates them (Fischer-Kowalski and Huttler, 1998).

When comparing the concepts used in energetic socioeconomic metabolism and in material flow analysis, it becomes obvious that although material flow analysis includes all materials flows necessary to produce societal stocks, the energy required to power the materials flows is not represented. The analysis of Taiwan's socioeconomic metabolism using both material flow analysis and emergy synthesis provided indicators to overview the material flows and energy flows of Taiwan's ecological economic system (Table 6). The ratio of total material use to total emergy used decreased over time. This represents the role of consumption of material flows in Taiwan's socioeconomic metabolism is decreasing (Fig. 9). Moreover, the system imports more materials from foreign countries as seen in the increased ratio of imported material flows to total material use. However, despite the increase of imported material flows, the ratio of imported material flows to total imported emergy decreased indicating that the importance of imported material flows diminished among all imported resources (material flows, energy flows and services). Finally, the ratio of exported material flows to total material flows increased reflecting the export-oriented policies of Taiwan's socio-economy.

Changes in material flows in human societies are only made possible though an increased appropriation and use of energy. The ratio of total material use to total energy use was

Table 6
Indicators of socioeconomic metabolism

Indicators	1981	1986	1991	1996	2001
1. Emergy evaluation of material flows					
(1) Ratio of total material use to total emergy used	1.05	1.08	0.89	0.68	0.64
(2) Ratio of imported material flows to total emergy used	0.24	0.32	0.28	0.25	0.22
(3) Ratio of domestic material flows to total material use	0.77	0.71	0.69	0.64	0.65
(4) Ratio of domestic extracted non-renewable material to total material use	0.08	0.05	0.05	0.04	0.02
(5) Ratio of imported material flow to total material flows	0.23	0.29	0.31	0.36	0.35
(6) Ratio of imported non-renewable materials to total material use	0.04	0.05	0.05	0.05	0.08
(7) Ratio of imported material flow to total imported emergy	0.41	0.52	0.37	0.33	0.28
(8) Ratio of exported material to total material flows	0.22	0.26	0.22	0.32	0.41
(9) Ratio of exported non-renewable material flows to total material flows	0.13	0.17	0.12	0.21	0.31
(10) Ratio of exported material flows to total exported emergy	0.91	0.88	0.83	0.81	0.84
2. Dependency of material and emergy flows					
(1) Ratio of total material use to total energy use	1.86	2.07	1.58	1.12	0.97
(2) Ratio of total non-renewable material flow to total energy use	0.21	0.21	0.16	0.11	0.10
(3) Ratio of imported material to imported energy	0.75	1.28	0.70	0.59	0.45
(4) Ratio of imported non-renewable to imported energy	0.13	0.22	0.11	0.09	0.11
3. Efficiency and intensity of socioeconomic metabolism					
(1) Per GDP total material use (kg)	1.33	0.89	0.54	0.50	0.50
(2) Per GDP total material use ($\times 10^{12}$ sej)	3.87	3.28	1.70	1.10	1.18
(3) Per GDP total emergy used ($\times 10^{12}$ sej)	3.69	3.04	1.93	1.62	1.85
(4) Per capita total material use (kg)	3422	3683	4768	6506	6055
(5) Per capita total material use ($\times 10^{16}$ sej)	1.00	1.35	1.51	1.42	1.43
(6) Per capita total emergy used ($\times 10^{16}$ sej)	0.95	1.26	1.71	2.10	2.24
(7) Per capita non-renewable materials used (kg)	1945	2250	3303	5143	4898
(8) Per capita non-renewable materials used ($\times 10^{15}$ sej)	1.14	1.37	1.52	1.33	1.47
(9) Per capita non-renewable emergy used ($\times 10^{16}$ sej)	0.45	0.53	0.92	1.11	1.35

over 1.0 from 1981 to 1996 which indicates the important role that material flows have played (Fig. 10). However, that ratio has decreased to 0.97 in 2001 indicating that energy is starting to play an ever more important role in Taiwan's socioeconomic system. Taiwan is facing a transformation in its resource consumption where more energy and fewer materials are being used. Without consideration of energy flows material flow analysis alone would not recognize this phenomenon. Another important observation related to material and energy is that the ratio of imported material flows to imported energy is less

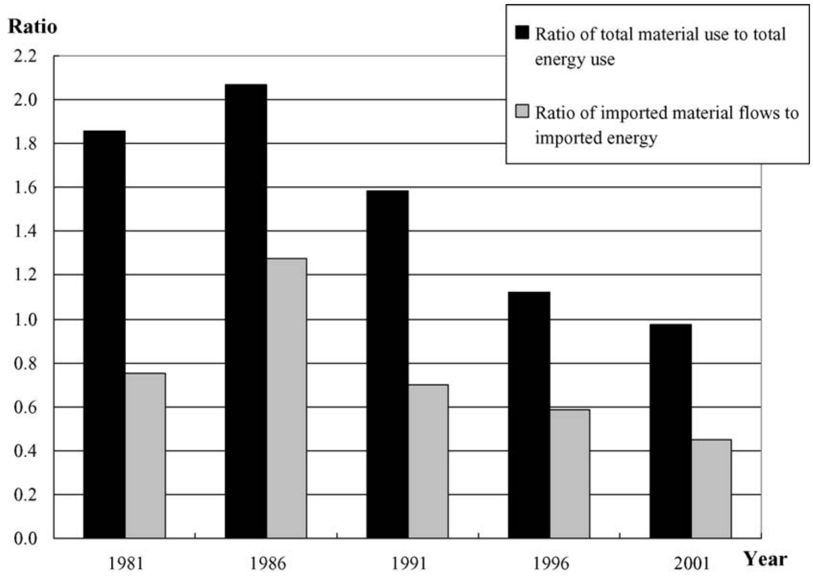

Fig. 10. Role of energy consumption in Taiwan's socioeconomic metabolism.

than 1.0 from 1991 to 2001. This ratio indicates that dependency on imported energy is increasing.

Total material use per unit of economic product (TMU/GDP) are a familiar indicator of progress in production techniques in material flow analysis. The mass-based TMU/GDP for Taiwan decrease from 1981 to 1991 and then became stable from 1991 to 2001 suggesting that the production efficiency of industries in Taiwan improved from 1981 to 1991 but has not changed significantly from 1991 to 2001 (Fig. 11). However, from an emergy point of view, the decreasing emergy-based TMU/GDP reveals that the emergy purchasing power of Taiwan's GDP has decreased. This is evidence that Taiwan's socioeconomic system has evolved from traditional manufacturing industries to a higher industrialized society. Furthermore, mass-based TMU/pop shows that the people in Taiwan consumed increasing amounts of materials from 1981 to 1996 and that this consumption then decreased from 1996 to 2001. Similarly the emergy-based TMU/pop began to decrease in 1991. The reason for the increase of mass-based TMU/pop and decrease in emergy-based TMU/pop from 1991 to 1996 is that Taiwan's socioeconomic system consumed significant amounts of materials from a lower energy hierarchical level (e.g. sand and gravel) for rapid urbanization.

4.3. Socioeconomic metabolism versus land use transformation

Understanding land use change is an interdisciplinary effort. In order to understand the cause and effects of changes in land use or land cover, it is essential to bridge the gap between natural sciences and social sciences. This requires integrating social, economic,

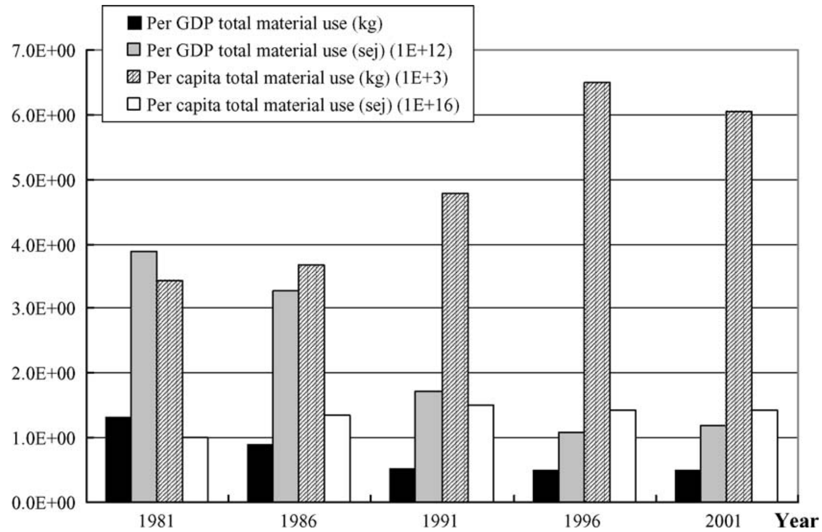

Fig. 11. Total material use in Taiwan.

and cultural causes of land use change with evaluations of its biophysical nature and consequences. Land use can be regarded as human influence and control to provide inputs and infrastructure needed to maintain socioeconomic metabolism. The change of land use to yield goods and services represents the most substantial human intervention of the Earth ecosystem by altering its interaction with the surrounding biophysical environment. The conceptual framework of socioeconomic metabolism could serve as a basis for such theoretical integration (Haberl et al., 2001).

Industrial modernization can be regarded as a process that is characterized as a shift in energy use that has caused significant impacts on human land use practices and socioeconomic metabolism (Krausmann, 2001). This paper establishes several indicators of emergy flow per area to investigate the relationships of the change of socioeconomic metabolism with land use change in Taiwan. Table 7 summarizes the results of our analysis. Due to Taiwan's mountainous terrain and demand of land for urban and industrial use, its agriculture has been intensively practiced. The productivity of agricultural area increased from 1.28×10^{17} sej in 1981 to 2.06×10^{17} sej in 2001. However, due to excess production and decreasing demand for rice, the emergy value of rice production per area of rice field decreased. The decrease was in large part the result of a government policy of fallowing to reduce the amount of cultivated land. The relation between energy input and output of rice production has fallen dramatically during Taiwan's industrialization. The decrease energy return from rice production has made rice production an energy-consuming instead of energy-producing sector. The emergy value of the production of other crops and livestock, as well as aquaculture all increased during the past 20 years. The subsidies of fossil energy have intensified agricultural practices and increased the productivity of agriculture on smaller agricultural areas. Due to the decreasing production of sugarcane, the overall productivity of agricultural area is decreasing, but the increase of the higher emergy prod-

Table 7
Relations of socioeconomic metabolism and land use

	1981	1986	1991	1996	2001
1. Productivity of agricultural area (t/km^2)	1702.49	1642.63	1526.08	1417.79	1278.82
Productivity of agricultural area ($\times 10^{19}$ sej/km^2)	1.28	1.790	2.03	1.86	2.06
2. Productivity of rice field (t/km^2)	457.89	396.85	365.71	320.94	285.53
Productivity of rice field ($\times 10^{18}$ sej/km^2)	2.01	1.75	1.61	1.41	1.26
3. Productivity of crops (t/km^2)	3289.00	2814.28	2480.79	2430.94	1947.56
Productivity of crops ($\times 10^{19}$ sej/km^2)	1.28	1.36	1.34	1.39	1.38
4. Productivity of livestock products (t/km^2)	0.00	31722.99	41220.40	29029.80	35072.52
Productivity of livestock products ($\times 10^{20}$ sej/km^2)	0.00	7.49	9.73	6.85	8.28
5. Productivity of aquaculture (t/km^2)	2636.97	3112.71	3459.27	3231.31	3361.70
Productivity of aquaculture ($\times 10^{20}$ sej/km^2)	1.88	2.22	2.46	2.30	2.39
6. Empower density of urban area ($\times 10^{19}$ sej/km^2)	6.22	7.08	9.84	12.93	14.57
7. Consumption of sand/gravel and cement in urban area (t/km^2)	17865.05	16959.28	25018.07	42546.94	32757.37
Consumption of sand/gravel and cement in urban area ($\times 10^{20}$ sej/km^2)	2.86	2.56	3.08	3.22	2.19

	1981–1986	1986–1991	1991–1996	1996–2001
8. Amplifier ratio of sand/gravel and cement (t/km^2)[a]	134186.71	245558.45	851928.08	470382.96
Amplifier ratio of sand/gravel and cement ($\times 10^{18}$ sej/km^2)[a]	20.27	30.20	64.57	31.42

[a] (Δsand/gravel and cement)/Δurban area.

ucts such as aquaculture, vegetables and fruits has resulted in the reversed trend of higher emergy production per area.

During the period of 1992–1996, Taiwan's government underwent a "Six-Year National Development Plan", which triggered many public construction projects. The indicators of "consumption of sand and gravel and cement per urban area" and "the ratio of increase of the consumption of sand and gravel and cement to the increase of urban area" peaked the period of 1991 and 1996. The "empower density of urban area" increased from 6.22×10^{19} sej in 1981 to 14.57×10^{19} sej by 2001. Fig. 12 shows the positive relations between the emergy value of the increase of total material use with the increases in urban area. The transitions in the major features of socioeconomic metabolism are reflected in land use changes. Rapid economic growth in Taiwan triggered changes in land use and resulted in a transformation of the country's socioeconomic metabolism. Fig. 13 summarizes the overall trend of land use change and material and energy flows in Taiwan. The emergy value of material consumption (total material use (TMU) − export of material (EMF); see Table 3) was highest in 1991

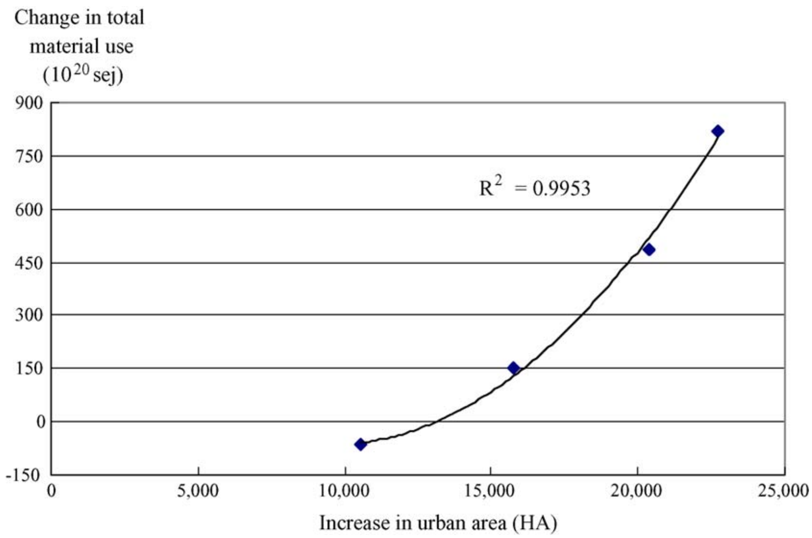

Fig. 12. Relations between increase in urban area and increase in total material use.

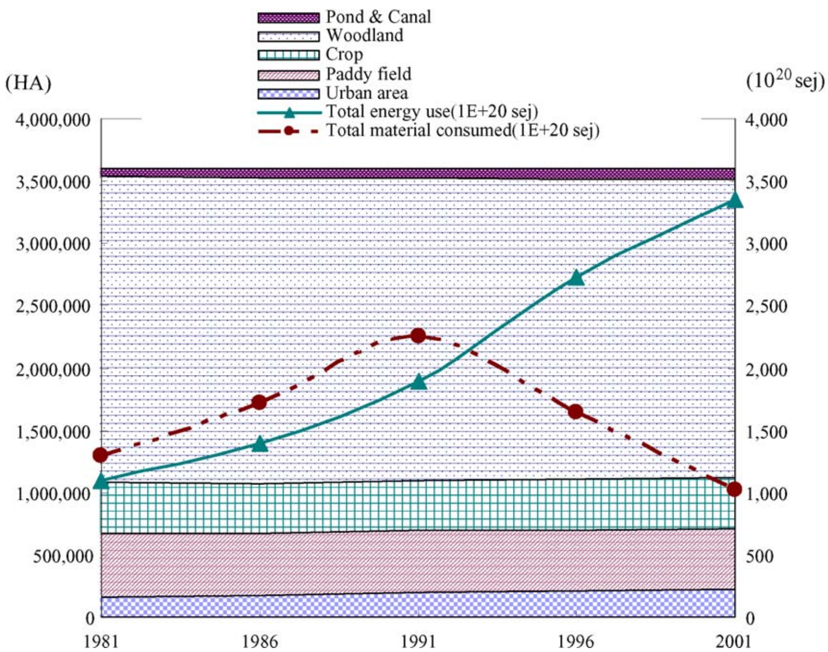

Fig. 13. Tread of land use change and material and energy flow.

and has been decreasing ever since. Conversely, the total energy requirements have been continuously increasing as a result of the increase of urban area.

5. Conclusion

Instead of developing material flow accounting and energy flow accounting systems separately, this research develops an energetic socioeconomic system analysis, which extends from material flow analysis by including energy flows and incorporating emergy evaluation to account for both material and energy flows on a common energy unit basis. The empirical analysis of materials flows presented here for Taiwan is based on periodically available statistical data sources. We started by defining categories of materials flows, including domestic renewable extraction, domestic non-renewable extraction, imported non-renewable, imported renewable, exported materials, etc. We analyze relations between socioeconomic metabolism and land use change of Taiwan during 1981–2001, thereby covering the period during which Taiwan's economy was growing rapidly.

In the methodological comparison of material flow analysis and emergy synthesis, because the indirect flows of unused extraction are included in estimates of total amount, it is not easy to recognize where these flows go. Due to the lack of information on these indirect flows, this paper did not calculate their emergy. The categories in material flow analysis do not contain renewable energy flows, electricity used, and services, which play increasingly important roles in Taiwan's socioeconomic metabolism. Given the trend of resource use toward fewer materials and more energy, the fact that renewable energy flows, electricity use, and services are omitted in material flow analysis leads to a bias in the evaluation of socioeconomic metabolism.

The second goal of this paper was to illustrate, for the case of Taiwan, some limitations of material flow analysis, and to demonstrate the usefulness of an emergy synthesis of socioeconomic metabolism. After completing an emergy synthesis of Taiwan's socioeconomic metabolism and comparing indicators calculated from mass against similar indicators calculated with emergy, we found that material flow analysis was unable to identify Taiwan's increasing dependence on energy use. We contend that the material flow analysis alone will not adequately describe socioeconomic metabolism without increased attention to energy flows. In the comparison of material flow analysis and emergy synthesis indicators for Taiwan, material flow indicators do not recognize the quality difference of materials consumed. This was particularly important for Taiwan where more materials with lower energy hierarchy have been utilized since 1991 to support rapid urbanization and the construction of public infrastructure. Our analysis shows that the emergy concept can contribute to systematizing the interrelations of society and its natural environment for the analysis of energy flows. Further, emergy synthesis can be useful in comparing the relative worth of materials flows in the ecological economic system. Emergetic perspective of socioeconomic metabolism can compensate for the often criticized aggregation by one single unit of mass for material flow analysis.

The reorganization of our land use and the reshaping of socioeconomic metabolism is critical to improving the sustainability of societies. To what extent do changes in socioeconomic metabolism trigger changes in land use, or do changes in land use lead to transformations of socio-economic metabolism? Haberl et al. (2001) suggest that the study on the relationship between land use and socioeconomic metabolism must be approached from dynamic and spatial analysis. Our results show that there is an intimate relationship between trends in socioeconomic metabolism and changes in land uses. Rapid economic growth changes the function of land use, which then affects the society's metabolism. However, this research lacks sufficient information to investigate whether changes in socioeconomic metabolism in Taiwan has triggered the land use changes. Furthermore, this paper can only used statistical land use data to analyze land use changes and its relationship to socioeconomic metabolism. Future research using land use change on a metropolitan scale is needed to study the effect of urban sprawl on socioeconomic metabolism.

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References

Adams RN. The eighth day: social evolution as the self-organization of energy. Austin, TX: University of Texas Press; 1988.

Ayers R, Kneese AV. Production, consumption and externalities. Am Econ Rev 1969;59:282–97.

Boyden S, Millar S, Newcombe K, O'Neill B. The ecology of a city and its people: the case of Hong Kong. Canberra: Austria National University Press; 1981.

Brown MT, Ulgiati S. Emergy and environmental accounting. In: Cleveland C, editor. Encyclopedia of energy, vol. 2. Amsterdam: Elsevier; 2004. p. 329–53.

Costanza R, d'Arge R, de Groot R, Faber S, Grasso M, Hannon B, et al. The value of the world's ecosystem services and natural capital. Nature 1997;387:253–60.

Eurostat. Economy-wide material flow accounts and derived indicators: a methodological guide. Luxembourg: Eurostat, European Commission; 2001.

Fischer-Kowalski M. Society's metabolism: the intellectual history of materials flow analysis. Part I. 1860–1970. J Ind Ecol 1998;2(1):61–78.

Fischer-Kowalski M, Haberl H. Tons, joules, and money: modes of production and their sustainability problems. Soc Nat Resour 1997;10:61–85.

Fischer-Kowalski M, Huttler W. Society's metabolism: the intellectual history of materials flow analysis. Part II. 1970–1998. J Ind Ecol 1998;2(4):107–36.

Giampietro M, Cerretelli G, Pimentel D. Energy analysis of agriculture ecosystem management: human return and sustainability. Agric Ecosyst Environ 1992;38:219–44.

Haberl H. The energetic metabolism of societies. J Ind Ecol 2001;5(1):11–31.

Haberl H, Batterbury S, Moran E. Using and shaping the land: a long-term perspective. Land Use Policy 2001;18:1–8.

Haberl H, Fischer-Kowalski M, Krausmann F, Weisz H, Winiwarter V. Progress towards sustainability? What the conceptual framework of material and energy flow accounting (MEFA) can offer. Land Use Policy 2004;21(3):199–213.

Hall CAS, Cleveland CJ, Kauffmann R. Energy and resource quality: the ecology of the economic process. New York: John Wiley and Sons; 1986.

Huang S-L, Hsu W-L. Material flow analysis and emergy evaluation of Taipei's urban construction. Landscape Urban Plann 2001;53:145–61.

Huang S-L, Odum HT. Ecology and economy: emergy synthesis and public policy in Taiwan. J Environ Manage 1991;32:313–33.

Krausmann F. Land use and industrial modernization: an empirical analysis of human influence in the functioning of ecosystem in Austria 1830–1995. Land Use Policy 2001;18:17–26.

Krausmann F, Haberl H, Schulz NB, Erb K-H, Darge E, Gaube V. Land-use change and socio-economic metabolism in Austria. Part I. Driving forces of land-use change 1950–1995. Land Use Policy 2003;20:1–20.

Lin S-S. Preliminary study on material-flow system and its establishment in Taiwan. International Trade. Master Thesis. Taiwan: Chung-Yuan Christian University; 2000 (in Chinese).

Martinez-Alier J. Ecological economics: energy, environment and society. Oxford: Basil Blackwell; 1987.

Meadows D, Meadows D, Jorgen R. The limits to growth. New York: Universe Books; 1972.

Odum HT. Environment, power and society. New York: John Wiley and Sons; 1971.

Odum HT. System ecology. New York: John Wiley and Sons; 1983.

Odum HT. Self-organization, transformity, and information. Science 1988;242:1132–9.

Odum HT. Environmental accounting—emergy and environmental decision making. New York: John Wiley and Sons; 1996.

Rappaport RA. The flow of energy in an agricultural society. Sci Am 1971;224(3):117–33.

Schandl H, Schulz N. Changes in the United Kingdom's natural relations in terms of society's metabolism and land-use from 1850 to the present day. Ecol Econ 2002;41:203–21.

Stahmer C, Kuhn M, Braun N. Physiche input–output-tabellen (PIOT) 1990. Wiesbaden: Statistisches Bundesamt; 1997.

Wernick I, Ausubel JH. National material flows and the environment. Annu Rev Energy Environ 1995;20:463–92.

Wolman A. The metabolism of cities. Scientific American; 1965. p. 179–88.

World Resources Institute. The weight of nations: material outflows from industrial economics. Washington, DC: World Resource Institute; 2000.