Chapter 2
Ecological Energy Accounting for Macao's Socioeconomic and Ecological Systems

2.1 Social and Economic Characteristics of Macao

China's Macao special administrative region is located on the western coast of the Pearl River estuary (Fig. 2.1). It lies between 111°31′33″E and 111°35′43″E, and between 22°06′39″N and 22°13′06″N. The city is located near the southern edge of the northern hemisphere's tropics and therefore lies near the southern hemisphere's tropics. As a result, Macao's average annual temperature is 22.3 °C, and the wind comes from opposite directions in winter and summer. The temperate climate is warm and wet in summer, with frequent tropical typhoons during both the summer and the autumn. Winter comes in January and February each year, and temperatures may drop below 4 °C, with a low amount of rainfall.

Macao is a unique Asian city, and has been the site of more than 400 years of cultural exchange between the western world and Chinese civilization (Maritime Administration 2005). In 2010, Macao's population was 544 600 (DSEC 1984–2011, 2011 data). The annual number of tourist arrivals averages 26 times the local population (DSEC 1984–2011, 2005 data). Macao has been expanding for many years since 1990 by means of progressive land reclamation along the coast to meet the needs of socioeconomic development. In 2010, the area reached 29.7 km^2, and comprised the Macao Peninsula (9.3 km^2), Taipa (6.8 km^2), Coloane (7.6 km^2), and the Cotai Reclaimed Land (6.0 km^2). The population density of Macao was about 18 337 persons per km^2 in 2010. The Macao Peninsula and Taipa are linked by three bridges, whereas Taipa and Coloane are connected by reclaimed land. Macao is therefore a small region, with a high population density and a large number of tourist visits annually.

Because Macao is characterized by a cultural mixture between the Western world and China that has developed over the past 400 years, "The Historic Centre of Macao", which has more than 20 monuments, was added to UNESCO's list of World Cultural Heritage sites in July 2005 (ICGRAEM 2006).

The currency is the Macao pataca (MOP), which is generally held at a constant ratio with the Hong Kong dollar of 1.032 to 1, so its value is also controlled by fluctuations in the U.S. dollar. (In the rest of the book, all economic values are

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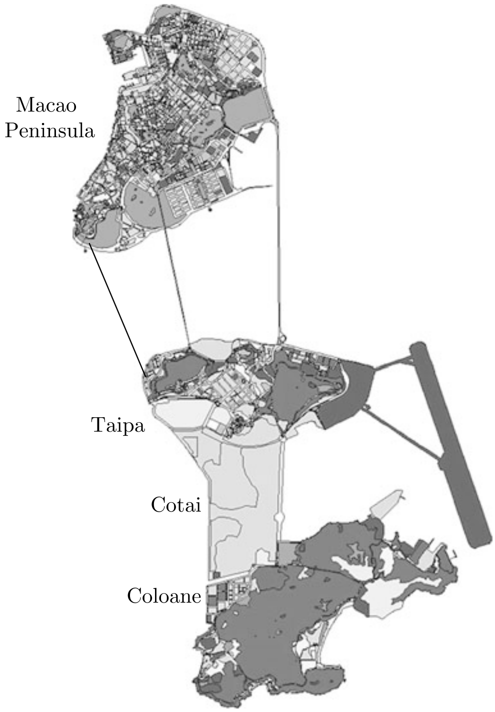

Fig. 2.1 Macao comprises the Macao Peninsula, Taipa, Cotai, and Coloane. (The map is based on the 2008 boundaries)

expressed in U.S. dollars unless otherwise noted.) The major products exported from Macao are ready-made garments, which account for about 70 % of total exports, and textile products. The main export markets are the United States, the EU, Hong Kong, and mainland China. The imported goods are mainly raw materials and partially finished products as well as consumer goods. Imported goods mainly originate from mainland China, Hong Kong, the EU, Japan, and the United States.

Since 1990, Macao has increasingly become a consumer society, following the abandonment of agriculture and the decline of the local fishing industry. Although most of the daily necessities of life, such as fresh water, food, fuel, raw materials, and goods, are imported, Macao's economy has maintained a robust growth rate with sustained prosperity as a result of the gaming and tourism industries.

Macao's government has implemented an economic development strategy that designated the tourism and gaming industries as the leading engines for economic growth (Wikipedia 2012). These industries are supported by a service sector, with parallel development of other sectors designed to develop a more diversified economy. By capitalizing on its particular geographic and socioeconomic advantages, Macao is making every effort to become a hub for regional trade, and particularly to support economic cooperation between mainland China and Portuguese-speaking countries and cooperation with expatriate Chinese entrepreneurs.

Despite these plans for diversification, the gaming and tourism industries contribute the largest single portion of the region's overall economic development.

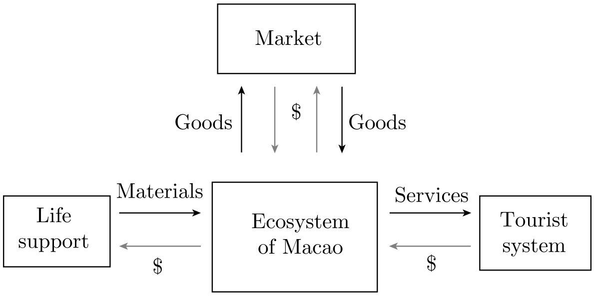

Fig. 2.2 Illustration of the flows of material and money for Macao's ecosystem. *Dark arrows* represent flows of goods, materials, and services; *light arrows* represent monetary flows

Gaming tax revenues alone account for 40 % of the government's total tax revenues, and about one-third of the total workforce is employed in this industry.

Macao's government opened the gaming industry to the private sector in 2002 by issuing three gaming concessions, which attracted many investors both at home and from North America and Hong Kong. With this liberalization of the gaming industry, the government expected to bolster other related industries, but also expected to benefit Macao's overall economic development.

Macao's economy has maintained robust growth and sustainable prosperity based on the gaming and tourism industries, which we will refer to as the "tourism" industry in the rest of this chapter. In 2004, real GDP reached $\$9.97 \times 10^9$ (DSEC 1984–2011, 2005 data). Tourism, manufacturing, finance and insurance, and construction and real estate have been the four pillars of Macao's economy since 1980. Tourism has been the main driver of development since the mid-1990s. The booming tourism industry contributed gaming tax receipts of $\$1.9 \times 10^9$ in 2004 (DSEC 1984–2011, 2005 data). The Mainland and Macao Closer Economic Partnership Arrangement (CEPA), which was implemented in 2004, has benefited many sectors of Macao's economy, but especially the tourism sector; the "free individual traveler" provision alone was responsible for tremendous growth of the number of tourists from mainland China (DSEC 1984–2011, 2005 data). Gambling is legal in Macao, but not in China, and previously, Chinese citizens were strictly limited from entering Macao. Under this provision, residents of most Chinese cities can now legally travel to Macao for gambling.

Figure 2.2 illustrates the exchanges between the three essential natural and socioeconomic components of Macao's ecosystem. The life-support system is represented by the block on the left side of the diagram. Almost all raw materials, foods, and water flow into Macao, whereas most money (currency) flows in the opposite direction as it leaves Macao to pay for the imported materials. The tourist system is represented by the block on the right side of the diagram. Tourists come to Macao to consume and to gamble, representing an import of money, whereas Macao's tourism sector supplies them with goods and services, which are mostly considered to be exports (as we discussed in Chap. 1). The external market is represented by the block

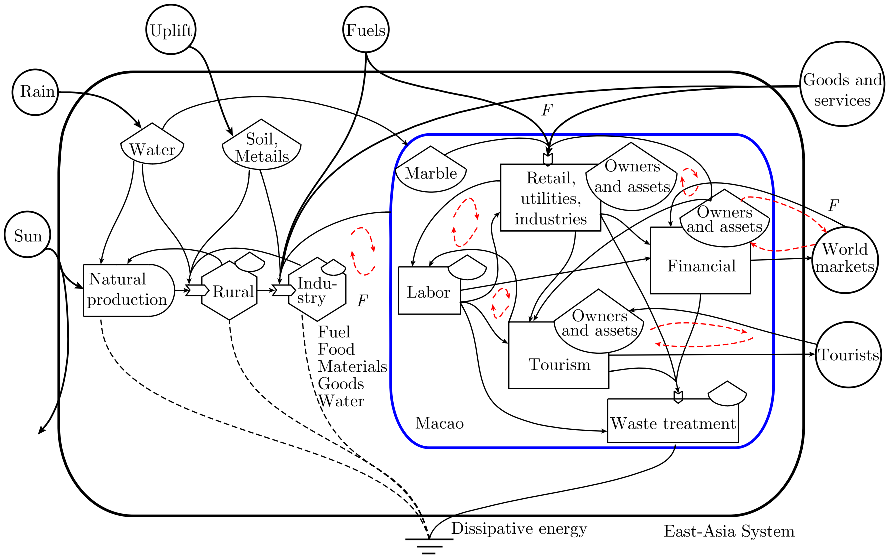

Fig. 2.3 Illustration of the materials, energy, and information transfer processes for Macao

at the top of the diagram. Macao exports its products to this market, and at the same time imports fuel, goods, and equipment that Macao does not produce internally.

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

2.2 Emergy Synthesis for Macao's Eco-economic System in 2004

Urban ecosystems consist of a large number of people living in close proximity. They serve as centers for both residential and commercial activities. The existence of a city or town and the maintenance of its internal structures depend on the inflow and outflow of the goods and services required to sustain these activities (Huang and Chen 2005). Despite their largely artificial nature, urban ecosystems exhibit the same basic kinds of interactions exhibited by other ecosystems. Most importantly, from the perspective of the living species contained by the urban ecosystem, none of these ecosystems are ecologically self-contained or self-sufficient; that is, all cities are sustained by life-support processes that occur mainly outside the city's boundaries.

Densely populated cities such as Macao could not exist without the support of a larger surrounding ecosystem (Huang and Odum 1996). We performed an emergy analysis for Macao to ensure that the importance of these external inputs was recognized in our analysis, and created a diagram (Fig. 2.3) that depicts the environmental resources provided by the natural area surrounding Macao. These resources are concentrated in rural areas, where solar energy is captured by plants and other organ-

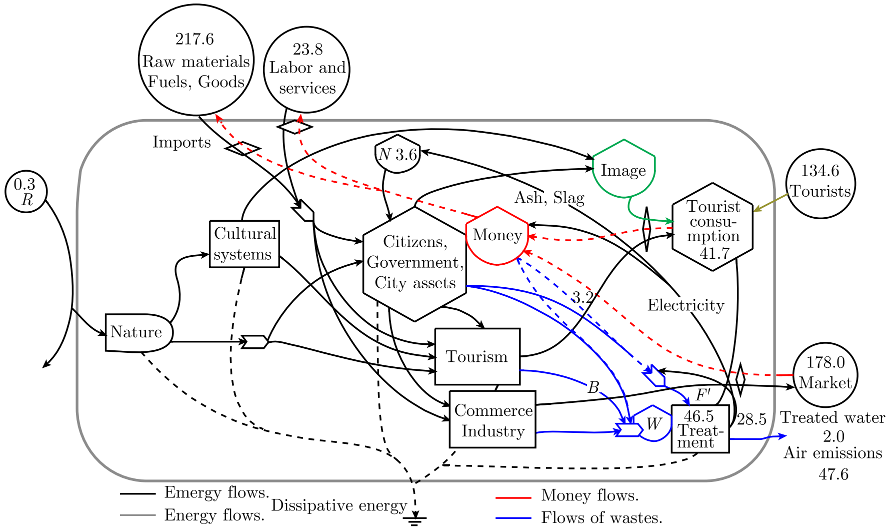

Fig. 2.4 A concise emergy flow diagram for Macao's ecosystem in 2004 (all values are $\times 10^{20}$ sej)

isms, accumulated (stored), and used to support the city of Macao, which exchanges emergy with the surrounding ecosystem (Huang and Odum 1996). In the case of our study area, Macao's life-support energy and materials are mostly provided by the surrounding areas of Mainland China. Figure 2.4 is a concise emergy-flow diagram for Macao's internal and external environment and economy.

Most of the data used in the remainder of this chapter were provided by DSEC (1984–2011, 2005 data), the Cartography and Cadastre Bureau of Macao (2012), the Meteorological and Geophysical Bureau of Macao (2006), and the Environment Council of Macao (ECM 2000, 2004, 2005).

Table 2.1 summarizes the flows of materials (imports and exports) for Macao in 2004. Imports totaled about 588×10^8 kg of fresh water annually, versus 29.3×10^8 kg of other goods and raw materials. This contrasts with exports of 551×10^8 kg of sewage discharged and 3.8×10^8 kg of products exported to regions outside Macao. We found that the total exports equaled only 0.6 % of the total imported materials (on a weight basis). Fresh water was the main imported material, and amounted to 95.3 % of the total weight of imported material. Raw and processed materials were the main exports, and accounted for 72.3 % of the total exports. About 98.2 % of the imported materials came from China, whereas only 48.0 % of the products were exported to China. The electricity imported from China totaled 151.3 GW · h in 2004.

In 2004, the total emergy used in Macao was 245.2×10^{20} sej, the imported emergy was 241.3×10^{20} sej, and the exported emergy was 136.3×10^{20} sej (Lei and Wang 2008b). Table 2.2 summarizes the renewable (R) and indigenous non-renewable resources (N) that contributed to these totals. They accounted for 0.1 % of the total emergy use (U) in 2004. The indigenous non-renewable environmental

Table 2.1 Material flows for Macao in 2004. Totals may not add up precisely due to rounding errors

Item	Imports ($\times 10^8$ kg)	% of total imports	Exports ($\times 10^6$ kg)	% of total exports	Sewage ($\times 10^9$ kg)	Solid wastes ($\times 10^9$ kg)
Water	588.49	95.3	0	0		
Food	3.36	0.5	7.2	1.9		
Fuels	7.47	1.2	276	0.01		
Minerals	8.99	1.5	12.4	3.25		
Raw and processed materials	5.41	0.9	275.6	72.3		
Goods	4.03	0.7	86.0	22.6		
Total	618.26	100.0	381.2	100.0	55.1	0.3

resources (N) of Macao comprised mined marble (3.60×10^{20} sej) and the loss of topsoil (1.19×10^{14} sej), which together accounted for about 1.5 % of Macao's emergy use in 2004. By using Eq. 1.11, we can calculate that Macao's net emergy was 63.6×10^{20} sej (Lei and Wang 2008b).

Table 2.3 summarizes the emergy trade exchange (imports versus exports), and Table 2.4 summarizes the emergy flows for Macao in 2004. Figure 2.4 shows imports of 23.8×10^{20} sej (labor and services), of 241.3×10^{20} sej of purchased emergy (F), and of 134.6×10^{20} sej of tourist payments for their consumption flowing into Macao to support the system's metabolism. The imported water and food accounted for 14.8 % of the emergy used, whereas the imported fuel, minerals, and electricity accounted for 12.3 % of the emergy used in 2004. The imports of purchased goods and raw materials (G, including water and food) accounted for 76.5 % of the emergy used, whereas the imported services accounted for 9.7 % of the emergy used. In 2004, the imported emergy (F) accounted for 98.4 % of the total emergy used. Inexpensive raw materials usually carry plentiful emergy, thus the E_m/\$ for China was 4.94×10^{12} sej $\$^{-1}$ in 2004 (Zhao 2002), versus only 2.38×10^{12} sej $\$^{-1}$ for Macao. Thus, when Macao exchanges goods with China that have the same total monetary value, more of the emergy assets flow into Macao. Analysis of other development projects (Ulgiati et al. 1995) suggests that one of the main driving forces behind international trade is the fact that developed countries benefit greatly from an unequal emergy exchange with developing countries when they exchange goods with the developing region. Unequal emergy exchange related to the primary materials provided by different regions will lead to an emergy surplus when spending the same amount of money (H. T. Odum 1996).

The consumer emergy of tourists:

$$M_t = R_t \times U = 0.17 \times 2.45 \times 10^{22} \text{ sej} = 4.17 \times 10^{21} \text{ sej}$$

Wastes were not included in the renewable resources category, since wastes are not exchanged. Figure 2.5 summarizes Macao's emergy flows. In 2004, Macao exported about 73.8 % of its total emergy used (U, including tourism consumption),

Table 2.2 Annual emergy flows for Macao's renewable and non-renewable resources in 2004

Item	Raw units	Transformity (sej per raw unit)	Source of published value for transformity	Emergy (sej)	Emdollars (em$)
Renewable					
1. Sunlight[a]	1.16×10^{17} J	1	H. T. Odum (1996)	1.16×10^{17}	4.85×10^{4}
2. Wind, kinetic[b]	2.22×10^{14} J	1470	Campbell (2004)	3.27×10^{17}	1.37×10^{5}
3. Rain, chemical[c]	2.06×10^{14} J	18 100	Campbell (2004)	3.73×10^{18}	1.56×10^{6}
4. Rain, geopotential[d]	4.09×10^{13} J	10 300	Campbell (2004)	4.21×10^{17}	1.76×10^{5}
5. Waves[e]	8.9×10^{14} J	25 900	H. T. Odum (1996)	2.31×10^{19}	1.12×10^{7}
6. Earth cycle[f]	3.99×10^{13} J	33 700	Campbell (2004)	1.34×10^{18}	5.63×10^{5}
Total (3 + 5 + 6)	1.11×10^{15} J		–	2.71×10^{19}	1.14×10^{7}
Non-renewable					
7. Marble	3.60×10^{11} g	1 000 000 000	H. T. Odum (1996)	3.60×10^{20}	1.51×10^{8}
8. Topsoil loss	1.90×10^{9} g	62 500	H. T. Odum (1996)	1.19×10^{14}	4.98×10
Total (7 + 8)	3.62×10^{11} g		–	3.60×10^{20}	1.51×10^{8}

[a]Sunlight: Energy (J) = (area of country) × (mean insolation) × (1 − albedo) × conversion factor (kcal to J) = $(2.75 \times 10^{7}\ m^2) \times (1.31 \times 10^{6}\ kcal\ m^{-2}\ y^{-1}) \times (1 - 0.2) \times (4186\ J\ kcal^{-1}) = 1.16 \times 10^{17}\ J\ year^{-1}$

[b]Wind, kinetic: Energy (J) = (area) × (air density) × (drag coefficient) × ($velocity^3$) × conversion factor (years to seconds) = $(2.75 \times 10^{7}\ m^2) \times (1.3\ kg\ m^{-3}) \times (1.00 \times 10^{-3}) \times (5.83\ m\ s^{-1}) \times (3.15 \times 10^{7}\ s\ year^{-1}) = 2.22 \times 10^{14}\ J\ year^{-1}$

[c]Rain, chemical: Energy (land, J) = (area) × (rainfall) × (water density) × (Gibbs number) = $(2.75 \times 10^{7}\ m^2) \times (1.52\ m) \times (1000\ kg\ m^{-3}) \times (4.94 \times 10^{3}\ J\ kg^{-1}) = 2.06 \times 10^{14}\ J\ year^{-1}$

[d]Rain, geopotential: Energy (J) = (area) × (rainfall) × (water density) × (mean elevation) × (acceleration due to gravity) = $(2.75 \times 10^{7}\ m^2) \times (1.52\ m\ year^{-1}) \times (1000\ kg\ m^{-3}) \times (763\ m) \times (9.8\ m\ s^{-2}) = 4.09 \times 10^{13}\ J\ year^{-1}$

[e]Waves: Energy (J) = (shoreline length) × (1/8) × (density of seawater) × (acceleration due to gravity) × $(wave\ height)^2$ × (wave velocity) × conversion factor (years to seconds) = $(4.086 \times 10^{4}\ m) \times (1/8) \times (1.025 \times 10^{3}\ kg\ m^{-3}) \times (9.8\ m\ sec^{-2}) \times (0.5\ m)^2 \times (2.21\ m\ s^{-1}) \times (3.14 \times 10^{7}\ s\ year^{-1}) = 8.94 \times 10^{14}\ J\ year^{-1}$

[f]Earth cycle: Energy (J) = (area) × (heat flow) = $(2.75 \times 10^{7}\ m^2) \times (1.45 \times 10^{6}\ J\ m^{-2}\ year^{-1}) = 3.99 \times 10^{13}\ J\ year^{-1}$

Table 2.3 The evaluation of emergy imports and exports by Macao in 2004

Item	Raw units (g)	Quantity	Transformity (sej per unit)	Reference for transformity value	Emergy ($\times 10^{20}$ sej)	Emdollars (em$)
Imports						
1. Foods	3.36×10^{11}	3.52×10^{15} (J)	38 categories	See Table A.1[a]	39.15	7.94×10^{8}
2. Fresh water	5.88×10^{13}	2.91×10^{14} (J)	660 000	Lan et al. (2002)	1.92	3.88×10^{7}
3. Electricity	151 GW · h	5.45×10^{14} (J)	159 000	H. T. Odum (1996)	0.87	1.76×10^{7}
4. Fuels	7.47×10^{11}	3.10×10^{16} (J)	54 000	H. T. Odum (2000)	16.70	1.01×10^{9}
5. Minerals	9.50×10^{11}	9.50×10^{11} (g)	9 categories	See Table A.2[b]	12.57	2.55×10^{8}
6. Raw and processed materials	5.41×10^{11}	3.18×10^{15} (J)	38 categories	See Table A.3[c]	120.77	7.27×10^{9}
7. Goods	4.03×10^{11}	2.92×10^{11} (J)	34 categories	See Table A.4[d]	25.66	1.54×10^{9}
Total (1–7)	6.18×10^{13}	3.86×10^{16} (J)	–	–	217.65	1.09×10^{10}
Exports						
1. Foods	7.22×10^{9}	9.87×10^{13} (J)	27 categories	See Table A.5[e]	0.99	4.17×10^{7}
2. Fuels	2.76×10^{7}	1.16×10^{12} (J)	54 000	H. T. Odum (2000)	0.00	2.63×10^{4}
3. Cement	1.24×10^{10}	1.24×10^{10} (g)	2.07×10^{9}	See Table A.6[f]	0.26	1.07×10^{7}
4. Raw materials	2.76×10^{11}	2.90×10^{15} (J)	37 categories	See Table A.7[g]	121.36	5.10×10^{9}
5. Goods	8.60×10^{10}	7.08×10^{10} (J)	30 categories	See Table A.8[h]	13.68	5.75×10^{8}
Total (1–5)	3.81×10^{11}	3.00×10^{15} (J)	–	–	136.29	5.73×10^{9}

Table 2.3 (*Continued*)

Item	Raw units (g)	Quantity	Transformity (sej per unit)	Reference for transformity value	Emergy ($\times 10^{20}$ sej)	Emdollars (em$)
Service imports and tourism exports		$	E_m/$		Emergy	Emdollars
1. Service imports (P_2I_3)		1.43×10^9 ($)	4.94×10^{12}	Zhao (2002)	23.77	9.99×10^8
2. Service exports (Tourism income, T_m)[i]		8.10×10^9 ($)	1.66×10^{12}	Abel (2000)	134.56	5.66×10^9
3. Tourist consumption (M_t)[j]		The tourists consumed 17.4 % of the total emergy used (U)			42.60	1.79×10^9
Waste emergy	Mass	Heat value (kcal kg^{-1})	Transformity (sej J^{-1})	–	Emergy	–
1. Solid wastes	2.56×10^8 (kg)	6.07×10^6	1.80×10^6	Zhao (2002)	28.00	1.18×10^9
2. Sewage	5.51×10^{10} (kg)	4.91×10^3	6.66×10^5	Zhao (2002)	1.80	7.57×10^7

[a] Imported food was classified into 38 categories, and the results of the emergy calculation process are listed in Table A.1

[b] The imported and exported items were classified into various categories, and the results of the emergy calculation process are listed in Table A.2

[c] The imported and exported items were classified into various categories, and the results of the emergy calculation process are listed in Table A.3

[d] The imported and exported items were classified into various categories, and the results of the emergy calculation process are listed in Table A.4

[e] The imported and exported items were classified into various categories, and the results of the emergy calculation process are listed in Table A.5

[f] The imported and exported items were classified into various categories, and the results of the emergy calculation process are listed in Table A.6

[g] The imported and exported items were classified into various categories, and the results of the emergy calculation process are listed in Table A.7

[h] The imported and exported items were classified into various categories, and the results of the emergy calculation process are listed in Table A.8

[i] The exported tourism emergy was calculated according to Eq. 1.13. The global transformity value was obtained from M. T. Brown (University of Florida, Gainesville, personal communication, 2004)

[j] According to Eqs. 1.14 and 1.15:

$$R_t = \frac{16\,672\,600 \times 1.1 \times 1.9}{16\,672\,600 \times 1.9 \times 1.1 + 365 \times 465\,333} = 0.17$$

Table 2.4 Summary of emergy flows for Macao in 2004

Variable	Explanation	Energy or mass or money	Solar emergy (sej)	Emdollars (em$)
R	Renewable resources	1.11×10^{15} (J)	2.71×10^{19}	1.14×10^{7}
N	Non-renewable resources	3.62×10^{11} (g)	3.60×10^{20}	1.51×10^{8}
Fuel	Imported fuels and minerals	3.16×10^{16} (J)	3.05×10^{21}	1.28×10^{9}
G	Imported foods, goods, and raw materials	7.03×10^{15} (J)	1.87×10^{22}	7.86×10^{9}
$P_2 I_3$[a]	Emergy of services from other places	1.43×10^{9} ($)	2.38×10^{21}	9.99×10^{8}
F (imported)	Imported emergy: Fuel $+ G + P_2 I_3$	3.86×10^{16} (J)	2.41×10^{22}	1.01×10^{10}
U[b]	Total emergy used: $R + N + F$	3.97×10^{16} (J)	2.45×10^{22}	1.03×10^{10}
B	Exported production	3.00×10^{15} (J)	1.46×10^{22}	5.73×10^{9}
Y (exported)	Exported emergy $(B + M_t)$[c]			
ELE	Electricity: 1880 GW·h	7.36×10^{15} (J)	1.45×10^{21}	6.10×10^{8}
GDP	Gross domestic product (US$)	1.03×10^{10} ($)		
W[d]	Waste emergy		2.98×10^{21}	
P_2	World E_m/$ ratio, used in imports		1.66×10^{12}	
P_1	Macao E_m/$ ratio		2.38×10^{12}	

[a] This calculation method is based on the method of H. T. Odum (1996)

[b] The total emergy used does not include tourism emergy so as to avoid double counting. The tourist consumption will increase the amount of imported materials (F)

[c] This equation is deduced from Fig. 2.5

[d] Waste emergy here includes the emergy of sewage and solid wastes

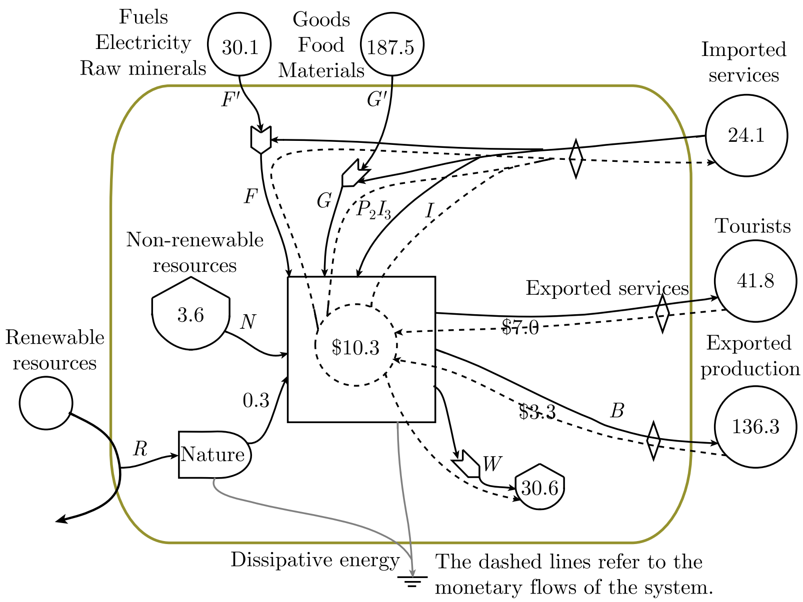

Fig. 2.5 Summary of Macao's emergy flows in 2004. Values with no units of measurement are $\times 10^{20}$ sej year^{-1} (Lei and Wang 2008b)

and the production component (P) accounted for about 56.5 % of the imported emergy (F). Exported products that supported the human labor expended in the production activities as well as in providing other services totaled 136.29×10^{20} sej. Textiles were the main exported products, and accounted for 96.5 % of the total exported emergy (Lei and Wang 2008b).

Macao has a high wastes emergy ($W = 30.8 \times 10^{20}$ sej) based on combining the embodied emergy in wastes (29.8×10^{20} sej) with the treatment inputs and services (1.0×10^{20} sej) for the sewage and solid wastes that the city produces. Reducing Macao's environmental impact despite its limited area has become an important goal to ensure long-term sustainable development. We will discuss this further in Chap. 6.

"Unfair" emergy exchanges, in which one partner in the exchange benefits more than the other, bring plentiful net emergy benefits into the boundaries of Macao's system. In 2004, Macao's gross net emergy surplus was 146.78×10^{20} sej. This resulted from the following four exchange processes (Table 2.4, Fig. 2.6):

1. The tourism income was $\$8.10 \times 10^9$; the equivalent emergy was 134.56×10^{20} sej, whereas Macao only provided 41.74×10^{20} sej of goods and services for the tourists. This resulted in an emergy surplus of 92.82×10^{20} sej.
2. The imported labor and services cost $\$1.43 \times 10^9$. Macao paid for 34.04×10^{20} sej of this emergy, and gained only 23.77×10^{20} sej of emergy in return. The net emergy loss was therefore 10.27×10^{20} sej in this exchange process.

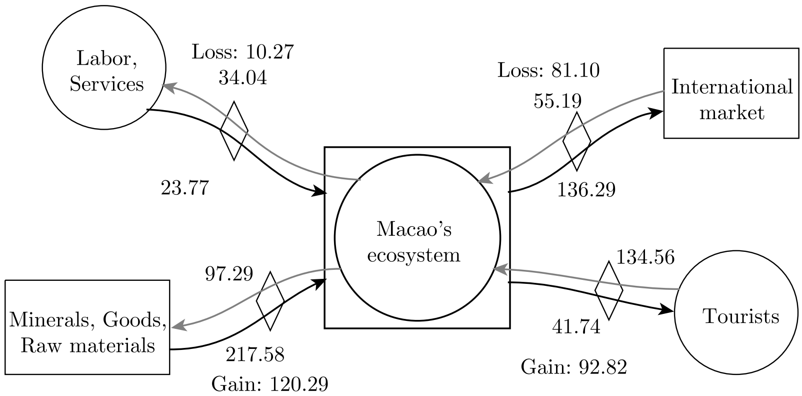

Fig. 2.6 Summary of the emergy exchange between Macao and the external systems that interact with the city in 2004 (all values are $\times 10^{20}$ sej. Macao's net emergy totaled 146.78×10^{20} sej in 2004)

3. The embodied emergy of imported goods and raw materials was 217.58×10^{20} sej, with only \$4.09 $\times 10^9$ (converted to 97.29×10^{20} sej) paid for this exchange. Thus, these imports generated a net emergy surplus of 120.29×10^{20} sej in import process.
4. The exports of products to the international market equaled 136.29×10^{20} sej, which earned Macao \$3.32 $\times 10^9$ (for an equivalent emergy of 55.19×10^{20} sej). Thus, a net emergy loss of 81.10×10^{20} sej occurred as a result of these exports.

The exchanges between Macao's tourism industry and the large number of tourists produced a large excess of emergy. Since this point is so important, we will discuss it further in Chap. 4.

2.3 Comparison of the Emergy-Based Indices of Five Cities

The preceding examination of Macao's emergy flows shows the insights into a city's ecosystem that can be obtained from emergy accounting. This approach provides additional insights when it is used to compare two or more cities. To provide an example of these insights, we compared the following four cities with Macao using data from previous studies (Lei et al. 2008):

- Taipei (Huang and Hsu 2003)
- Zhongshan (Zhao 2002)
- Miami-Dade County (Woithe 1995)
- San Juan (Doherty 1995)

Taipei is located in the northern part of Taiwan, and is the island's key urban center. The city has an area of about 2325 km^2, and its total population is approximately 6.3 million, having increased by about 25 % during the past decade. On average, approximately 2×10^6 m^2 of building floor space per annum were constructed between 1981 and 1998, mainly in response to rapid urbanization. During recent decades, Taiwan has experienced rapid economic growth, with associated expansion of urban areas and high rates of per capita consumption. Its GDP reached $\$211.21 \times 10^9$ in 2002, and its successful economy was called one of the "four little dragons" in Asia. Most of its resources were imported from outside the city and from other countries due to a lack of indigenous natural resources (Huang and Hsu 2003).

Zhongshan is located in China's southern Guangdong province, and is also a newly developing city. The city covers an area of about 1800 km^2, and the total population in 2000 was approximately 1.34 million, of whom about 60 % live in the city, compared with 18.3 % in 1978. During the past 20 years, Zhongshan has experienced rapid growth in the manufacturing and electronics industries and in various types of services, accompanied by rapid expansion of its urban area. Its GDP reached $\$3.78 \times 10^9$ in 2000. Although the region around Zhongshan has an efficient agricultural support system, most of its resources and raw materials were imported from other areas of mainland China and from other countries (Zhao 2002).

Miami-Dade County is located in the southeastern part of the U.S. state of Florida. With a population of 1.94 million in 1990, it was the most populous county in the state. The county seat was Miami, which is located on the southeastern seacoast of Florida, in the northeastern part of the county. Miami-Dade County covers a total area of 5060 km^2. During the 1960s, Miami became a major center of finance and trade with Latin America. The energy maintaining the county's structure was largely of external origin, and was purchased using income obtained from tourism, transfer payments from the U.S. federal government, investment activities, and retirement benefits from the large population of retired citizens who live in this region (Woithe 1995). We could not find GDP data for 1990, but its GDP had reached $\$7.15 \times 10^9$ in 2003 (Washington Economics Group, Inc. 2004). Miami-Dade County has a large area of wetlands, including Everglades National Park, and has developed extensive agricultural resources and the exploitation of rich supplies of minerals. As a highly developed city, Miami-Dade County imported most of its life-support materials, and exported mainly services and technology.

San Juan is the capital of Puerto Rico, and is the nation's largest city. As of the 1992 census, it had a population of 1.71 million living in an area of 537 km^2. The dense city serves as a location for many historical buildings and other tourism resources. Today, San Juan serves as one of Puerto Rico's most important seaports, and is the island's manufacturing, financial, cultural, and tourist center. We could not find GDP data for the city alone, but in 1992, the GDP of Puerto Rico was $\$39.8 \times 10^9$ (Doherty 1995).

Table 2.5 compares the main emergy indicators for Macao with those of the four other cities. The comparison of the trade emergy and net emergy are shown in Fig. 2.7. We found that all five cities had a positive net emergy (i.e., they imported more emergy than they exported), and were therefore expanding. Taipei imported the most emergy and also had the highest net emergy.

Table 2.5 Comparison of the emergy indices for Macao, Taipei (China Taiwan), Zhongshan (China), Miami-Dade County (USA), and San Juan (Puerto Rico)

Index	Expression	Macao (2004)	Taipei (2002)	Zhongshan (2000)	Miami-Dade County (1990)	San Juan (1992)
Area	A (km^2)	22.75	2325.00	1800.00	5060.00	537.00
Population	P ($\times 10^6$)	0.47	6.30	1.34	1.94	1.71
Renewable emergy flows	R ($\times 10^{20}$ sej)	0.32	5.02	2.52	23.1	0.39
Non-renewable emergy flows[a]	N ($\times 10^{20}$ sej)	3.53	11.20	2.58	0.07	0.00
Imported emergy flows	F ($\times 10^{22}$ sej)	2.42	11.8	2.69	6.38	3.76
Emergy used (U)	$R + N + F$ ($\times 10^{22}$ sej)	2.46	11.9	2.74	6.61	3.76
Exported emergy (Y)	$P_1 E_3 + B + N_2$ ($\times 10^{22}$ sej)	1.80	2.92	1.88	0.05	1.43
Emergy yield ratio (EYR)	Y/F	0.743	0.249	0.699	0.082	0.380
Emergy exchange ratio (EER)	F/Y	1.35	4.02	1.43	121.90	2.63
The percentage of total emergy use accounted for by renewable resources (%Ren)	$(R/U) \times 100$ %	0.13	0.42	0.92	3.50	0.10
Proportion of total emergy use accounted for by purchased emergy	F/U	0.984	0.986	0.981	0.965	0.999

Table 2.5 (*Continued*)

Index	Expression	Macao (2004)	Taipei (2002)	Zhongshan (2000)	Miami-Dade County (1990)	San Juan (1992)
Proportion of total emergy use accounted for by free emergy	$(R+N_0)/U$	0.0157	0.0055	0.0186	0.0351	0.0010
Emergy investment ratio (EIR)	$F/(R+N)$	6.27	7.24	5.27	2.75	96.41
Emergy density	U/A ($\times 10^{13}$ sej m^{-2})	89.39	5.12	1.52	1.31	7.01
Emergy use per person	U/P ($\times 10^{16}$ sej person^{-1})	5.28	1.89	2.05	3.41	2.20
Environmental loading ratio (ELR)	$(F+N)/R$	743	234	108	27.6	964
E_m/\$ ratio	U/GDP ($\times 10^{12}$ sej \$$^{-1}$)	2.39	0.56	7.25	1.60	1.64
% of emergy use accounted for by electricity	(ELE/U) × 100 %	5.06	15.51	11.43	51.30	11.80
Fuel use per person	Fuel/P ($\times 10^{15}$ sej person^{-1})	3.63	1.6	2.59	4.38	7.75
Emergy sustainability index (ESI)	EYR/ELR ($\times 10^{-3}$)	1.00	4.30	6.50	0.30	0.39
Net emergy (NE)	$R+F-Y$ ($\times 10^{22}$ sej)	0.63	8.88	0.83	6.56	2.33
Net emergy ratio (NER)	$(R+F-Y)/U$	0.25	0.75	0.30	0.99	0.62
Waste emergy ratio	W/U	0.12	0.15	0.18	–	–

[a]Non-renewable resources (N) can be divided into three parts: N_0 is the dispersal into the rural environment, N_1 is concentrated use, and N_2 is direct exports (H. T. Odum 1996)

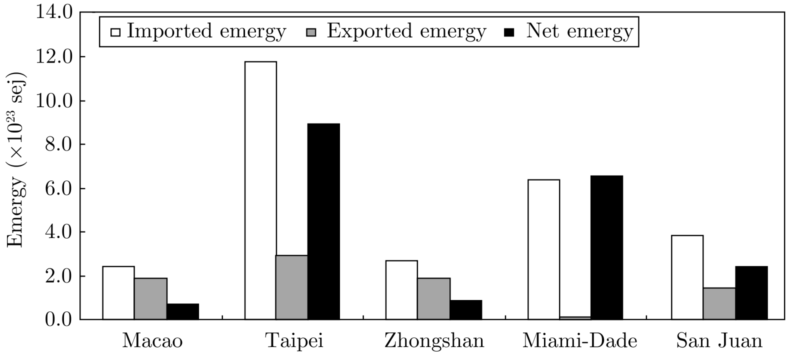

Fig. 2.7 A comparison of the import and export of emergy (and the resulting net emergy) of the five cities

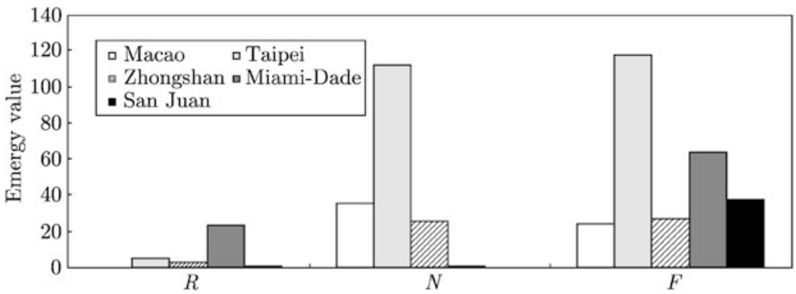

Fig. 2.8 Comparison of the renewable (R), non-renewable (N), and purchased emergy flows (F) for the five cities. *Note*: The three parameters use different units on the *y-axis*. R ($\times 10^{20}$ sej), N ($\times 10^{19}$ sej), F ($\times 10^{21}$ sej)

2.3.1 Comparison of the Emergy Components

Figure 2.8 visually compares the emergy components shown in Table 2.5. Because of a lack of local resources, all five cities imported most (more than 95 %) of the emergy they used (U). The proportion of U accounted for by purchased emergy ranged from 96.5 % (Miami-Dade County) to 99.9 % (San Juan), indicating that all five cities imported most of their used emergy.

2.3.2 Emergy Density, Emergy Use, and Fuel Use per Person

Figure 2.9 compares the emergy density, emergy use, and fuel use per person of the five cities. Macao's emergy use per person in 2004 (5.28×10^{16} sej; Table 2.5) was the highest of the five cities by a considerable margin (Fig. 2.9). Macao has one of the highest population densities in the world (Maritime Administration 2005),

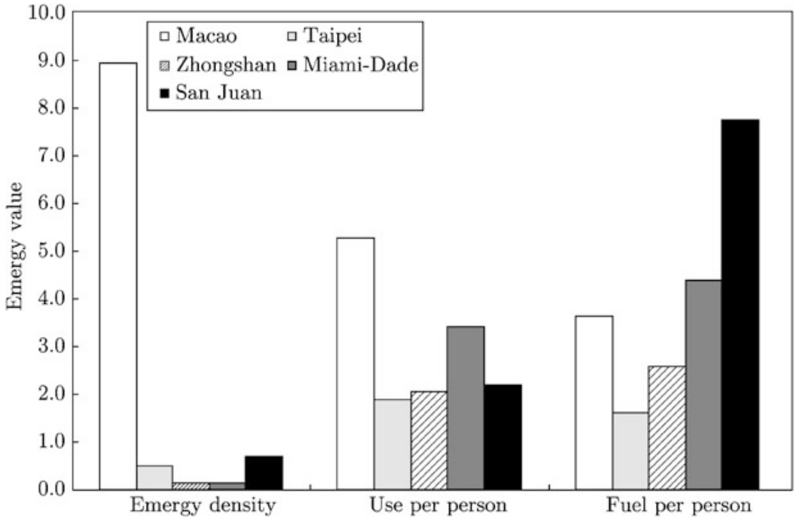

Fig. 2.9 Comparison of the emergy density and the per capita emergy and fuel use for the five cities. *Note*: The three parameters use different units on the *y-axis*. Emergy density ($\times 10^{14}$ sej/m^2), emergy use per person ($\times 10^{16}$ sej/person), fuel per person ($\times 10^{15}$ sej/person)

therefore its emergy density (89.4×10^{13} sej m^{-2}) was much higher than that of the other four cities. It was 17.5 times that of Taipei (5.1×10^{13} sej m^{-2}), 68.8 times that of Miami-Dade County (1.3×10^{13} sej m^{-2}), 59.6 times that of Zhongshan (1.5×10^{13} sej m^{-2}), and 12.8 times that of San Juan (7.0×10^{13} sej m^{-2}). Because of its small area, Macao had the highest emergy density, but San Juan had the highest average per capita fuel emergy use (7.75×10^{15} sej person^{-1}) of the five cities. Macao also had the highest emergy use per person. The large number of tourists consume many materials and services, thereby increasing the imported emergy. However, in contrast with the approach described in Chap. 1, this consumption was calculated by adding the average emergy consumption by local residents in order to use the same approach as in the other four studies and make the results comparable.

2.3.3 E_m/\$ Ratio and Emergy Investment Rate (EIR)

The E_m/\$ ratio represents the relationship between the emergy used and GDP, and it can thus indicate the levels of development and industrialization of a city (Table 2.5). A higher ratio implies that more resources would be consumed to produce the same GDP. Macao's E_m/\$ ratio in 2004 was 2.39×10^{12} sej \$$^{-1}$, which was lower than that of Zhongshan (7.25×10^{12} sej \$$^{-1}$) but higher than that of Miami-Dade County (1.60×10^{12} sej \$$^{-1}$), San Juan ($1.64 \times 10^{12}$ sej \$$^{-1}$), and Taipei ($0.56 \times 10^{12}$ sej \$$^{-1}$). In 2000, Zhongshan had experienced rapid industrial

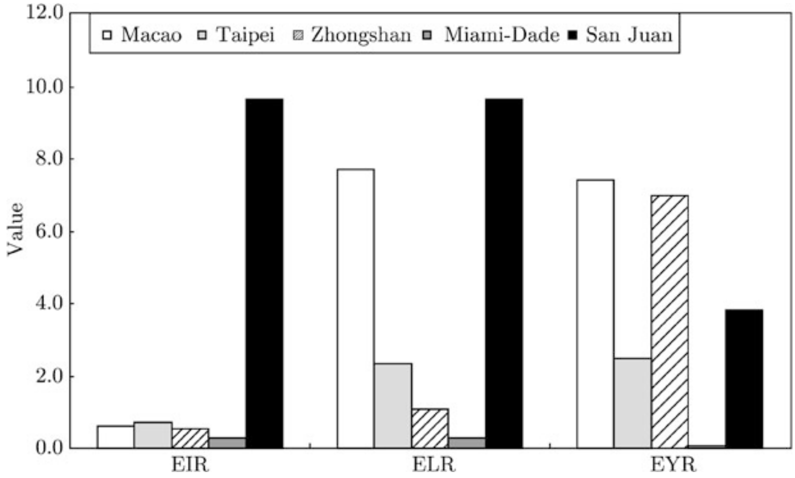

Fig. 2.10 Comparison of the emergy investment ratio (EIR), emergy yield ratio (EYR), and environmental loading ratio (ELR) of the five cities. *Note*: The three parameters use different units on the *y-axis*. ELR and EIR ($\times 10^2$), EYR ($\times 10^{-1}$)

development accompanied by intense use of a rich supply of natural resources, so its $E_m/\$$ ratio was the highest of the five cities. The high $E_m/\$$ ratio depressed the competitiveness of Macao's manufacturing industry, and higher prices forced many enterprises to move to South China in search of lower resource costs and lower salaries.

EIR equals the flows of imported emergy (F) from the economy divided by the indigenous emergy inputs ($R + N$). This index thus measures the intensity of economic development and the resulting load on the environment; it is useful for evaluating the relative contribution of free environmental inputs. A high ratio means that the environment is supporting a higher economic input than other regions with lower ratios. The EIR values for the five cities were all high, ranging from 2.75 (Miami-Dade County) to 96.41 (San Juan).

The emergy yield ratio (EYR) represents the ratio of output emergy (Y) to input emergy (F), so a lower ratio means more net emergy transferred into a city. Macao's EYR in 2004 was 0.74, which was higher than that of any of the other cities. This value means that an input of 1 sej will result in only 0.74 sej of output to the market outside the system. Miami-Dade County had the lowest ratio (0.08) of the five cities (Fig. 2.10).

2.3.4 Emergy Exchange Ratio (EER)

Emergy is an appropriate measure for evaluating the benefits to a nation from all types of international exchange (H. T. Odum 1996). By definition, an EER value greater than 1 means that the emergy received by the system exceeds the emergy the system provides to external systems. As a result, the system stores emergy, which will be advantageous for its survival and development. Table 2.5 shows that Macao had the smallest EER (1.35), followed by Zhongshan (1.43), San Juan (2.63), Taipei (4.02), and Miami-Dade County (121.9). The detailed values for San Juan and Miami-Dade County were not directly available in the published literature. Thus, to estimate the emergy yield (Y) for San Juan, we inferred the values for imported services, loans, and tourism from the data provided by Doherty (1995, p. 125, Table 1). Similarly, it was not possible to find published exported emergy values for Miami-Dade County, so the value was inferred from the data provided by Woithe (1995, p. 111, Table 3), and the resulting value may have been underestimated.

2.3.5 Renewable Resources Proportion (%Ren), Emergy Sustainability Index (ESI), and Net Emergy Ratio (NER)

The indicators and ratios developed by means of emergy analysis can account for both ecological and economic contributions, and permit international comparisons (Ulgiati and Brown 1998). %Ren is the proportion (%) of the total energy driving a process that is derived from renewable sources (i.e., $\%\text{Ren} = (R/U) \times 100\ \%$). In the long run, only processes with high %Ren are sustainable (Brown and Ulgiati 1997). %Ren can be used as a measure of the sustainability of a system: the higher the value, the higher the ability of the system to make use of the local available renewable resources (H. T. Odum 1996). Table 2.5 and Fig. 2.11 show that %Ren ranged from 0.1 % (San Juan) to 3.5 % (Miami-Dade County). Because these values are so small, comparing the cities based exclusively on %Ren would be ineffective because it would neglect the enormous emergy input that plays such an important role in these cities.

The ESI values of all five cites were well below 1, ranging from 0.3×10^{-3} for Miami-Dade County to 6.5×10^{-3} for Zhongshan. In a dense city such as Macao, ELR is usually very high because renewable resources inside the system are insufficient, which would produce a very small ESI (Table 2.5, Fig. 2.11). The NER values for Macao (0.25) and Zhongshan (0.30) were moderate, and suggest that both cities have attained a suitable ratio of regional development, whereas those of Taipei (0.75) and San Juan (0.62) were too high for sustainability. However, the biggest NER value was for Miami-Dade (0.99), and this value is so high that clearly too much weight has been placed on the foundation that underlies sustainability as a result of overexploitation of the surrounding regions that sustain the city.

2.4 Time Series for Macao's Emergy and Emergy-Based Indices

Emergy accounting can also be used to examine how a system's use of resources changes over time. Table 2.6 summarizes the changes in Macao's key emergy components and indicators from 1983 to 2004. In the remainder of this section, we will

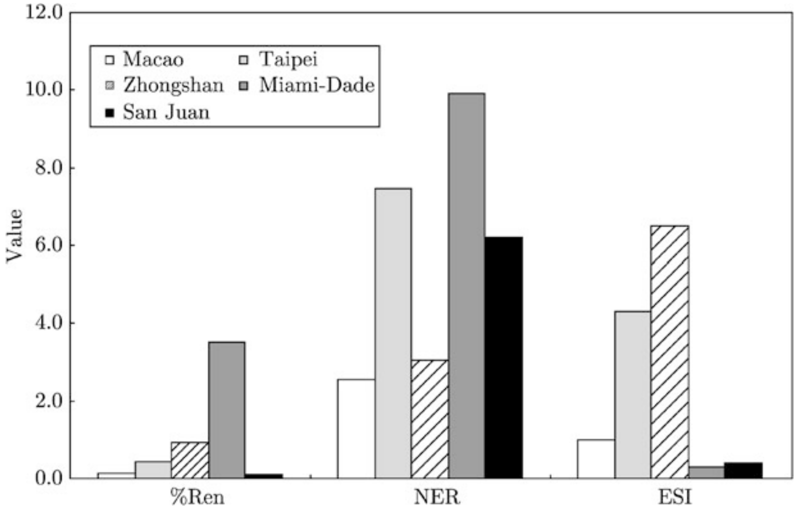

Fig. 2.11 Comparison of the proportion of renewable emergy (%Ren), the net emergy ratio (NER), and the emergy sustainability index (ESI) of the five cities. *Note*: The three parameters use different units on the *y-axis*, NER ($\times 10^{-1}$), ESI ($\times 10^{-3}$)

discuss the trends for individual emergy components and indicators during this period.

2.4.1 The Components of Emergy Use

Figure 2.12 presents the variations of the components of Macao's total emergy use (U) from 1983 to 2004. The emergy of raw materials was the largest imported item for Macao, and it increased as Macao's economy grew. The emergy of minerals was the second-largest imported item from 1985 to 1993, when food became the second-largest import. Table 2.6 summarizes the emergy components and indicators used for the years under study.

Figure 2.13 presents the variations in emergy flows in Macao's renewable and non-renewable resources and in water, electricity, and fuel consumption from 1983 to 2004. The non-renewable resources declined from 7.2×10^{20} sej in 1983 to 5.4×10^{20} sej in 1988, then decreased to 3.60×10^{20} sej in 1990 due to decreasing excavation of marble, and then remained at roughly the same level until 2004. The water and electricity consumption increased slowly throughout this period as the population increased. Fossil fuel consumption increased every year, from 4.98×10^{20} sej in 1983 to 16.70×10^{20} sej in 2004.

Figure 2.14 presents the variations in Macao's imports of minerals, raw materials, goods, food, and services from 1983 to 2004. The imports of food and services rose slowly during this period as the population increased. The emergy of goods fluctuated within a narrow range, but increased from 21.70×10^{20} sej in 1983 to

Table 2.6 Changes in Macao's emergy components and emergy-based indicators from 1983 to 2004

Item	Equation	1983	1985	1988	1990	1993	1995	1997	2000	2004
Renewable emergy ($\times 10^{20}$ sej)	R	0.274	0.264	0.258	0.253	0.270	0.266	0.286	0.286	0.271
Non-renewable emergy ($\times 10^{20}$ sej)	N_0	7.20	7.20	5.40	3.60	3.60	3.60	3.60	3.60	3.60
Imported emergy ($\times 10^{20}$ sej)	F	92.98	111.04	149.07	184.88	243.15	213.44	192.65	183.72	241.34
Total emergy used ($\times 10^{20}$ sej)	U	100.45	118.50	154.73	188.73	247.02	217.31	196.54	187.60	245.21
Exported emergy ($\times 10^{20}$ sej)	Y	71.44	92.06	118.29	133.07	132.94	120.00	107.17	135.62	178.03
Waste emergy ($\times 10^{20}$ sej)	W	8.74	8.95	9.76	10.30	21.00	21.70	25.08	26.50	49.42
%Ren	$(R/U) \times 100$	0.27	0.22	0.17	0.13	0.11	0.12	0.15	0.15	0.11
ESR (%)	$[(R + N_0)/U] \times 100$	7.44	6.30	3.66	2.04	1.57	1.78	1.98	2.07	1.58
EIR	$F/(R + N)$	12.4	14.9	26.3	48.0	62.8	55.2	47.0	47.3	62.3
ELR	$(N + F)/R$	366	448	598	745	915	817	687	655	904
Emergy density ($\times 10^{14}$ sej m^{-2})	U/area	6.47	7.00	9.14	10.90	12.80	10.35	9.16	7.39	8.92
Per capita emergy use ($\times 10^{14}$ sej person^{-1})	U/P	355.15	409.03	489.65	563.43	643.32	530.92	465.73	428.80	526.96
Per capita electricity use ($\times 10^{14}$ sej person^{-1})	Electricity/P	8.23	8.31	11.01	13.14	17.00	17.87	19.28	20.71	31.17
Per capita fuel use ($\times 10^{14}$ sej person^{-1})	Fuel/P	17.60	16.04	22.55	23.11	25.36	24.59	26.11	26.79	35.88
E_m/$ ratio ($\times 10^{12}$ sej \$$^{-1}$)	U/GDP	8.76	8.66	6.64	5.78	4.36	3.18	2.66	3.03	2.38
EYR	Y/F	0.77	0.83	0.79	0.72	0.55	0.56	0.56	0.74	0.74
ESI ($\times 10^{-3}$)	EYR/ELR	2.10	1.85	1.33	0.97	0.60	0.69	0.81	1.13	0.82
Net emergy ($\times 10^{20}$ sej)	$F + R - Y$	21.81	19.23	31.04	52.06	110.49	93.70	85.77	48.39	63.58
Net emergy ratio	Net emergy/U	0.217	0.162	0.201	0.276	0.447	0.431	0.436	0.258	0.259

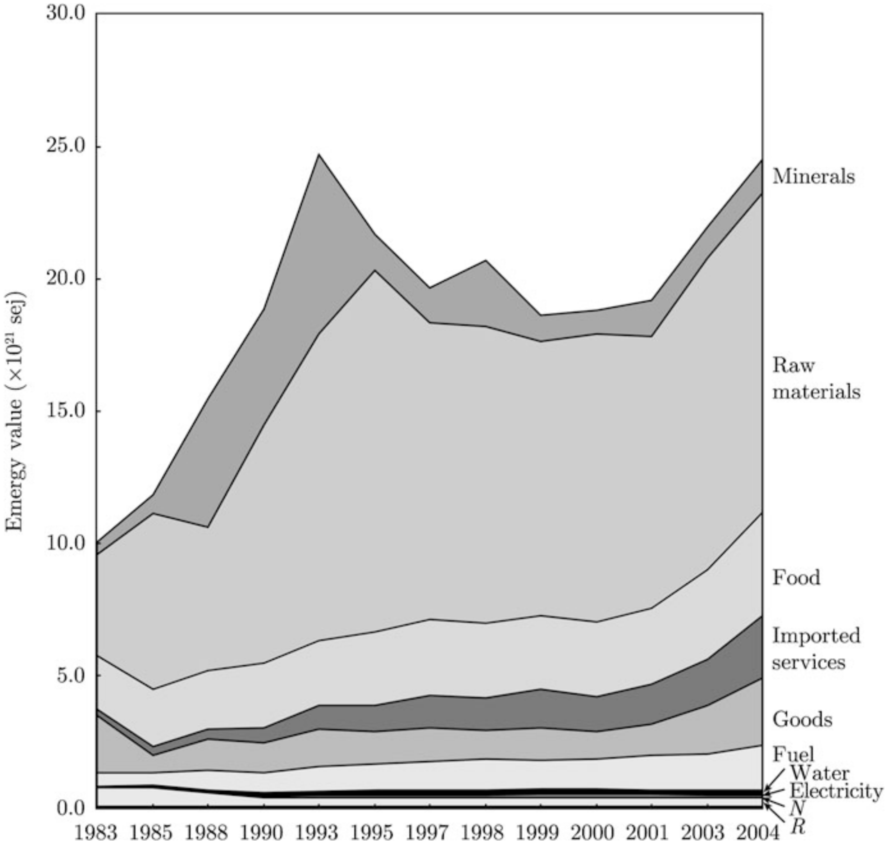

Fig. 2.12 Changes in the components of Macao's emergy use from 1983 to 2004

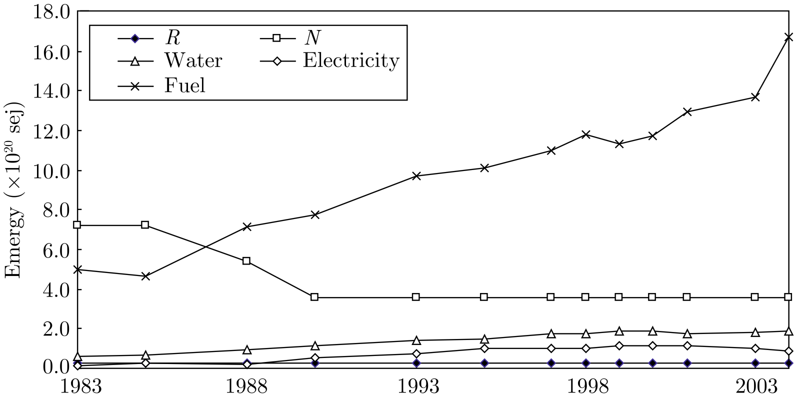

Fig. 2.13 The trends in emergy components (R, renewable resources; N, non-renewable resources; and water, electricity, and fuel) from 1983 to 2004

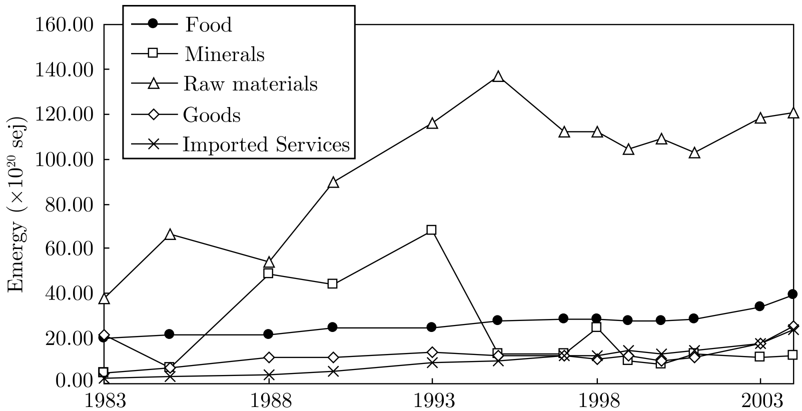

Fig. 2.14 Trends in Macao's imported emergy components from 1983 to 2004

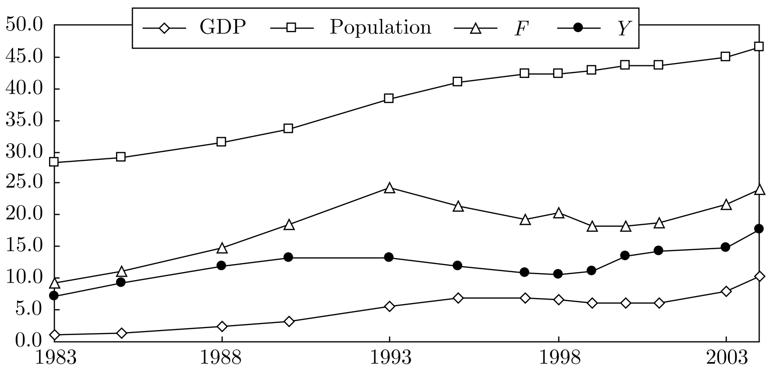

Fig. 2.15 Trends in Macao's GDP, population, imported emergy (F), and exported emergy (Y) from 1983 to 2004. *Note*: The four parameters use different units on the *y-axis*. GDP ($\times 10^9$ \$), Population ($\times 10^4$ persons), the other two parameters ($\times 10^{21}$ sej)

25.66×10^{20} sej in 2004, whereas the emergy of imported food rose from 20.00×10^{20} sej to 39.15×10^{20} sej.

The emergy of raw materials increased from 38.20×10^{20} sej in 1983 to a peak of 137.00×10^{20} sej in 1995, then decreased to 120.77×10^{20} sej in 2004. The emergy of minerals fluctuated during the study period, especially from 1985 to 1993, which was a period when infrastructure development and land reclamation were booming. The peak of Macao's development occurred in 1993, when mineral imports reached 50.93×10^{12} g, which was 5.28 times the 1992 value (9.65×10^{12} g) and 37.2 times the 1994 value (1.37×10^{12} g). In terms of the emergy value of these minerals, the value in 1993 (67.80×10^{20} sej) was 1.6 times the 1990 value (43.80×10^{20} sej), and 5.0 times the 1995 value (13.50×10^{20} sej). At that time, the high quantity of mineral imports raised the imported emergy (F), so the amount of emergy used (U) and the imported emergy (F) were also the highest in that year (Fig. 2.15).

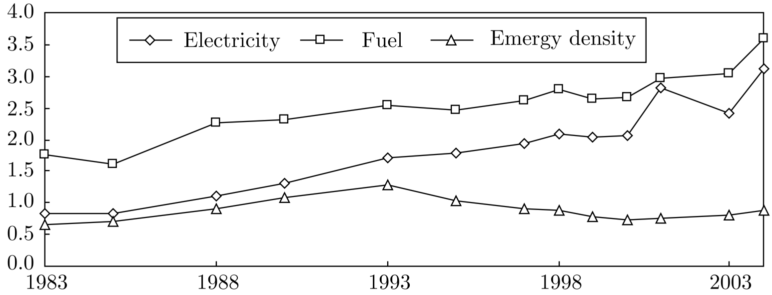

Fig. 2.16 Changes in Macao's per capita electricity and fuel consumption and its emergy density (U/area) from 1983 to 2004. *Note*: Per capita electricity and fuel emergy use the same units ($\times 10^{15}$ sej/person); emergy density uses different units ($\times 10^{15}$ m^{-2})

From 1983 to 1993, the population and GDP increased. During the same period, U, F and Y increased steadily (Fig. 2.15), while emergy density and average emergy also increased. After 1993, U, F, Y and emergy density began to decrease slowly until 2000, and then increased again (Fig. 2.16).

F increased from 92.98 $\times 10^{20}$ sej in 1983 to its peak of 243.15 $\times 10^{20}$ sej in 1993, decreased until 1999, and finally rose to 241.34 $\times 10^{20}$ sej in 2004. Simultaneously, Y increased from 71.44 $\times 10^{20}$ sej in 1983 to a peak of 132.94 $\times 10^{20}$ sej in 1993, decreased until 1999, and finally rose to 178.03 $\times 10^{20}$ sej in 2004. F increased more rapidly than Y, followed by GDP and population.

2.4.2 Per Capita Electricity Emergy, Fuel Emergy, and Emergy Density (U/area)

Macao's per capita electricity emergy increased from 8.23 $\times 10^{14}$ sej in 1983 to 31.17 $\times 10^{14}$ sej in 2004 (Fig. 2.16). During the same period, per capita fuel emergy increased from 17.60 $\times 10^{14}$ sej in 1983 to 35.88 $\times 10^{14}$ sej in 2004.

Macao's emergy density (U/area) increased from 6.47 $\times 10^{14}$ sej in 1983 to 12.80 $\times 10^{14}$ sej in 1993, declined to 7.39 $\times 10^{14}$ sej in 2000, and finally increased to 8.92 $\times 10^{14}$ sej in 2004. During this period, the population density decreased from 18 230 km^{-2} in 1983 to 16 961 km^{-2} in 2004 as a result of land reclamation.

2.4.3 %Ren and Emergy Self-sufficiency Ratio (ESR)

%Ren can be considered a measure of the sustainability of a system: the higher the value, the higher the ability of the system to make use of the local available renewable resources. For Macao, %Ren decreased steadily from 0.3 % in 1983 to 0.1 % in 2004 (Fig. 2.17). The city's ecosystem has a very low ability to provide sufficient emergy from inside its boundaries. R equaled only 2.71 $\times 10^{19}$ sej in

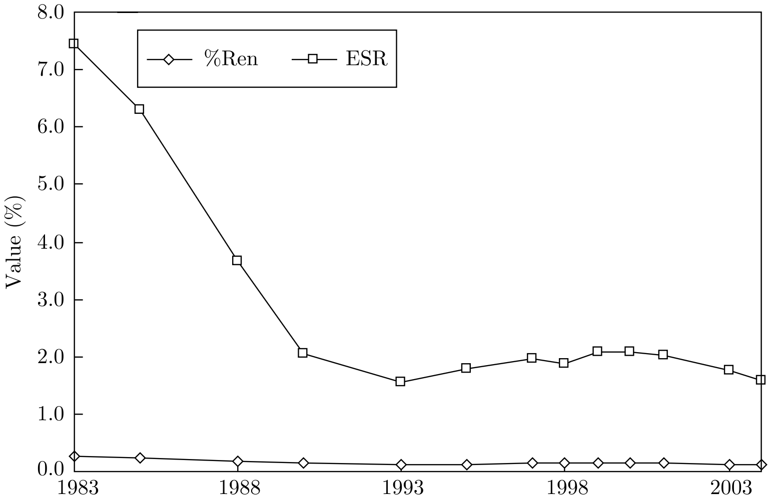

Fig. 2.17 Trends in Macao's proportion of renewable emergy (%Ren) and the emergy self-sufficiency ratio (ESR) from 1983 to 2004

2004. Thus, Macao's ESR, which equals $[(R + N_0)/U] \times 100\ \%$, was about 7.4 % in 1983, and decreased to 1.6 % in 2004.

2.4.4 Emergy Exchange Ratio (EER) and Emergy Yield Ratio (EYR)

EER can express the benefits of exchanges of emergy between Macao and its external environment. The larger the ratio, the more emergy Macao receives for every unit of emergy that it exports. EER varied greatly during the study period, increasing from 1.46 in 1983 to 2.42 in 1998, decreasing to 1.74 in 2001, and increasing to 2.11 in 2004 (Fig. 2.18). Simultaneously, EYR showed relatively little variation, decreasing from 0.77 in 1983 to 0.53 in 1998, then increasing to 0.74 in 2004.

2.4.5 Total Emergy Used (*U*), Emergy Money Ratio (E_m/$), Proportion of Waste Emergy (*W*), and Per Capita Emergy Use

U increased from 1.00×10^{22} sej in 1983 to a peak of 2.47×10^{22} sej in 1993, decreased to 1.88×10^{22} sej in 2000, then increased to 2.45×10^{22} sej in 2004 (Fig. 2.19). The per capita emergy use increased from 3.55×10^{16} sej in 1983 to 6.43×10^{16} sej in 1993, declined to 4.29×10^{16} sej in 2000, and then increased to

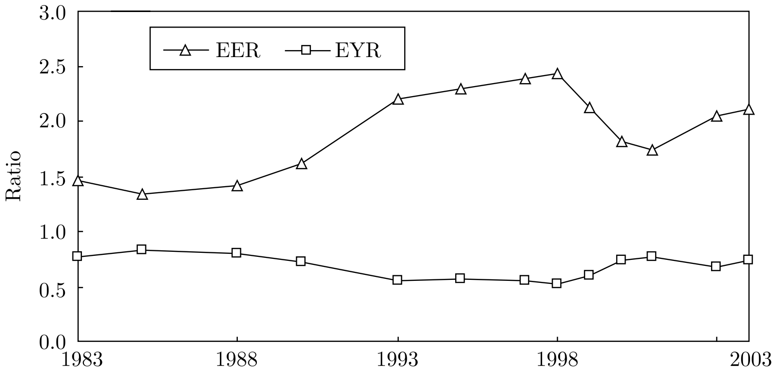

Fig. 2.18 Trends in Macao's emergy exchange ratio (EER) and emergy yield ratio (EYR) from 1983 to 2004

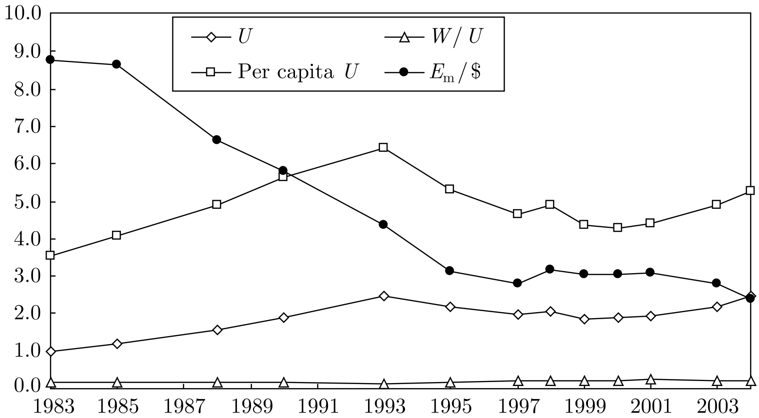

Fig. 2.19 Changes in Macao's total emergy used (U), the ratio of waste emergy to total emergy (W/U), the emergy money ratio ($E_m/\$$), and per capita U from 1983 to 2004. *Note*: The four parameters use different units on the *y-axis*. U ($\times 10^{22}$ sej), per capita U ($\times 10^{16}$ sej person^{-1}), $E_m/\$$ ($\times 10^{12}$ sej/\$ $^{-1}$)

5.27×10^{16} sej in 2004. $E_m/\$$ represents the relationship between the total emergy used and GDP. This ratio decreased steadily from 8.76×10^{12} sej \$$^{-1}$ in 1983 to 2.38×10^{12} sej \$$^{-1}$ in 2004, which was lower than the corresponding ratio for China in 2001 (4.94×10^{12} sej \$$^{-1}$; Zhao 2002) and higher than the ratio for the United States in 2000 (0.78×10^{12} sej \$$^{-1}$; Tilley 2005).

The gradual increase in waste emergy as a proportion of U during the study period (Fig. 2.19) indicated worsening environmental pressure. W/U increased from 0.16 in 1983 to 0.20 in 2004.

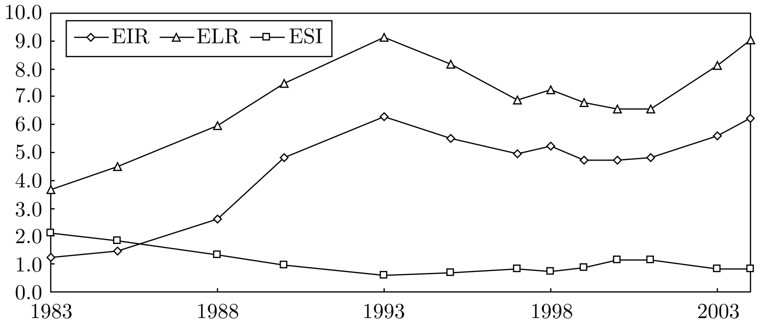

Fig. 2.20 Changes in Macao's emergy investment ratio (EIR), emergy loading ratio (ELR), and emergy sustainability index (ESI) from 1983 to 2004. *Note*: The three parameters use different units on the *y-axis*. EIR ($\times 10$), ELR ($\times 10^2$), ESI ($\times 10^{-3}$)

2.4.6 Emergy Investment Ratio (EIR), Environmental Loading Ratio (ELR), and Emergy Sustainability Index (ESI)

ELR is an indicator of the pressure on the local ecosystem and can be considered a measure of the level of ecosystem stress due to production activities (Ulgiati and Brown 1998). U and ELR fluctuated similarly in Macao during the study period. In the mid-1990s, GDP increased with increasing EIR and increasing ELR. $E_m/\$$ decreased from 8.76×10^{12} sej $\$^{-1}$ in 1983 to 2.38×10^{12} sej $\$^{-1}$ in 2004, which indicates that during this period, GDP increased faster than U, a phenomenon that also occurred in most other countries (Brown and Ulgiati 1997). Macao's per capita emergy used was 3.55×10^{16} sej in 1983, reached a maximum of 6.43×10^{16} sej in 1993, decreased to 4.29×10^{16} sej in 2000, and increased to 5.27×10^{16} sej in 2004. Macao's ESI was very small throughout the study period (less than 0.0021) and decreased from 1983 to 1993. In 1993, EYR remained stable while ELR reached its peak (915), thus ESI decreased to its lowest value (0.0006); thereafter, ESI increased until 2000 (0.0011) and then decreased until 2004 (0.0008; Fig. 2.20, Table 2.6). ESI was only 0.001 in 2004, versus values of 0.036 for Italy (Cialani et al. 2005) and 0.120 for Sweden (Hagström and Nilsson 2005). This comparison clearly indicates that Macao has a highly developed consumer system compared with the other countries. ESI decreased as the economy grew (i.e., as GDP increased) during the study period (Fig. 2.15).

Emergy-based indices are very different in cities than they are in large natural areas, where free renewable resources can be used to support the ecological system (Lan et al. 2002). This can be seen by comparing the value of an index such as ELR for Macao (904 in 2004) with that for the U.S. (5.85 in 2000; Professor Mark Brown, University of Florida, 2005, personal communication). Although the indices for small, dense areas such as Hong Kong, Singapore, and Macao differ from those of countries with vast territories, such as the United States, and are therefore not directly comparable, the magnitude of the difference in these values can still provide

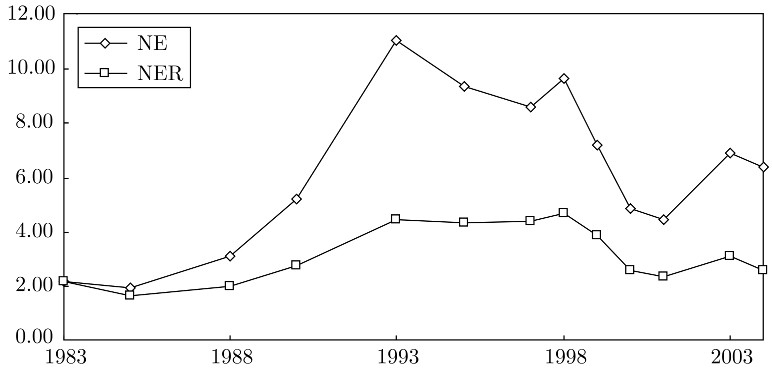

Fig. 2.21 Changes in Macao's net emergy (NE) and net emergy ratio (NER) from 1983 to 2004. The two parameters use different units on the *y-axis*. NE ($\times 10^{21}$ sej), NER ($\times 10^{-1}$)

insights into the relative ecological characteristics of two areas and can guide the development of suitable policies to improve sustainability.

2.4.7 Net Emergy (NE) and the Net Emergy Ratio (NER)

The NER values shown in Table 2.6 are a measure of the overall emergy exchange conditions for a study area. A high NER indicates a system that imports more emergy than it exports, accompanied by increased NE and improved welfare. NE increased from 2.18×10^{21} sej in 1983 to a peak value of 11.05×10^{21} sej in 1993, then decreased to 4.45×10^{21} sej in 2001, and increased again to 6.36×10^{21} sej in 2004 (Fig. 2.21, Table 2.6). These changes represent the benefits due to expansion of tourism and increased emergy imports. During the same time period, NER increased from 0.22 in 1983 to 0.45 in 1993 (Fig. 2.21, Table 2.6), which indicated that Macao earned a large part of its net emergy through international trade. Finally, NER decreased to 0.26 in 2004. In Macao, NER is therefore more an index of locally sustainable production than it is an emergy yield ratio.

Money is not real wealth, since real wealth includes food, minerals, fertile land, housing, information, arts, and other important factors (Ulgiati et al. 2004). Balancing the exchange of emergy between exports and imports may lead to more sustainable development for Macao in the long run (Brown and Ulgiati 2001) and may increase the real wealth of its citizens. The survival of a system depends on having a net emergy surplus (Ulgiati et al. 1995; Lei et al. 2006).

2.5 Time Series for Emergy Flows of Italy, Sweden, and Macao of China

Emergy synthesis can also be employed to evaluate macroeconomic conditions and the environment of regions ranging from cities that cover a large area to entire countries. In this section, we demonstrate this approach by comparing Macao with two other regions, with particular attention on how the emergy indicators changed over time in response to growth of a region's economy. In this comparison, we used research results for Italy (Cialani et al. 2005), Sweden (Hagström and Nelsson 2005), and Macao (our research). Table 2.7 summarizes the data used in this analysis. NE for all three regions remained positive throughout the study period (Figs. 2.22 to 2.27), which means that all three regions obtained more emergy than they exported. The positive NE will be advantageous for a region's development in the long term.

Macao is located on the western coast of China's Pearl River estuary. Although it is currently a special administrative region of China, Macao reflects more than 400 years of cultural exchanges between the western world and China. In 2004, Macao had a population of 465 333 and covered an area of 27.5 km^2 (DSEC 1984–2011, 2005 data). Tourism, manufacturing, the financial and insurance sector, and the construction and real estate sector were the four pillars of Macao's economy. Macao's economy has maintained a robust growth rate for the past three decades, largely due to sustained prosperity from the tourism sector.

Italy covers an area of 301 230 km^2, and had a population of 58 103 033 in 2002. It has a highly diversified modern industrial economy. Because of Italy's small size and high population, most of the raw materials needed by its industries and more than 75 % of its energy requirements are imported.

Sweden is one of the largest countries in Europe, with an area of 447 760 km^2. In 2002, its population was 9 001 774. Throughout the 20th century, Sweden has achieved one of the highest standards of living in the world as a result of its mixture of high technology and extensive natural resources. In particular, the combination of large size and small population make Sweden less dependent on imported emergy than many other countries of comparable size.

The three regions in this case study clearly represent different types of system: Macao is a high-density, high-consumption city, Italy is a developed country with insufficient internal natural resources to support its economy, and Sweden is rich in natural resources and has a small population. Table 2.7 summarizes the emergy indicators of all three countries or region since 1983 (Macao), 1984 (Italy), and 1956 (Sweden).

2.5.1 %Ren

Renewable resources are an important component of any system's sustainability because they will be replaced by natural processes after the passage of sufficient time. However, renewable resources are endangered by socioeconomic develop-

Table 2.7 Comparison of emergy indicators (EYR, emergy yield ratio; ELR, environmental load ratio; ESI, environmental sustainability index) and the net emergy (NE) and net emergy ratio (NER) for Macao of China, Italy, and Sweden. R, emergy in renewable resources; N, emergy in non-renewable resources; F, external inputs; Y, emergy yield ($= R + N + F$); U, total emergy consumption; %Ren, % of total emergy consumption provided by renewable emergy

Countries or region	Year	R ($\times 10^{21}$ sej)	N ($\times 10^{22}$ sej)	F ($\times 10^{23}$ sej)	Y ($\times 10^{23}$ sej)	U ($\times 10^{23}$ sej)	Population ($\times 10^{6}$)	GDP ($\times 10^{10}$ \$)	E_m/\$ ($\times 10^{12}$ sej \$$^{-1}$)
Macao of China	1983	0.03	0.07	0.09	0.06	0.10	0.28	0.12	8.76
	1985	0.03	0.07	0.11	0.09	0.12	0.29	0.14	8.66
	1988	0.03	0.05	0.15	0.12	0.16	0.32	0.23	6.64
	1990	0.03	0.04	0.19	0.13	0.19	0.33	0.33	5.78
	1993	0.03	0.04	0.24	0.13	0.25	0.38	0.57	4.36
	1995	0.03	0.04	0.21	0.12	0.22	0.41	0.69	3.13
	1997	0.03	0.04	0.18	0.11	0.19	0.42	0.70	2.66
	1998	0.03	0.04	0.20	0.11	0.21	0.42	0.65	3.12
	1999	0.03	0.04	0.18	0.11	0.19	0.43	0.61	3.06
	2000	0.03	0.04	0.18	0.13	0.19	0.44	0.62	3.03
	2003	0.03	0.04	0.22	0.15	0.22	0.45	0.79	2.782
Italy	1984	121.00	30.00	5.37	2.36	9.58	56.60	39.00	2.46
	1989	121.00	35.70	7.89	3.12	12.60	56.70	86.60	1.46
	1991	121.00	50.20	8.16	3.09	13.80	56.80	115.00	1.20
	1995	121.00	47.80	10.10	4.56	15.40	57.30	107.00	1.44
	2000	121.00	44.20	16.90	11.40	22.60	57.80	116.00	1.86
	2002	121.00	34.80	16.00	9.30	20.70	57.30	126.00	1.75
Sweden	1956	45.20	30.10	0.86	0.61	1.46	7.34	0.85	17.20
	1972	45.20	50.80	1.71	1.18	2.43	8.13	3.14	7.74
	1988	45.20	28.40	2.21	1.67	2.80	8.46	17.10	1.63
	1996	45.20	30.60	2.60	2.12	3.22	8.84	28.00	1.15
	2002	45.20	30.80	3.06	2.62	3.70	8.94	36.00	1.03

Table 2.7 (*Continued*)

Countries or region	Year	Emergy/capita ($\times 10^{16}$ sej)	EYR	ELR	ESI	%Ren	NE ($\times 10^{22}$ sej)	NER
Macao of China	1983	3.55	0.73	366.09	0.002	0.27	0.31	0.31
	1985	4.09	0.78	448.24	0.002	0.22	0.19	0.16
	1988	4.90	0.80	597.66	0.001	0.17	0.31	0.20
	1990	5.63	0.68	832.21	0.001	0.13	0.52	0.28
	1993	6.43	0.61	972.48	0.001	0.11	1.10	0.45
	1995	5.31	0.70	882.29	0.001	0.12	0.94	0.43
	1997	4.42	0.81	651.62	0.001	0.15	0.77	0.41
	1998	4.91	0.70	726.91	0.001	0.14	0.97	0.47
	1999	4.35	0.78	679.24	0.001	0.15	0.72	0.39
	2000	4.29	0.91	655.19	0.001	0.15	0.53	0.28
	2003	4.90	0.92	812.81	0.001	0.12	0.69	0.31
Italy	1984	1.69	1.78	6.91	0.260	12.63	42.20	0.44
	1989	2.23	1.61	9.47	0.170	9.60	59.60	0.47
	1991	2.44	1.76	10.46	0.170	8.77	62.70	0.45
	1995	2.69	1.59	11.72	0.140	7.86	67.30	0.44
	2000	3.90	1.33	17.65	0.080	5.35	67.10	0.30
	2002	3.60	1.29	16.13	0.080	5.85	78.70	0.28
Sweden	1956	1.99	1.71	2.23	0.765	30.96	5.52	0.38
	1972	2.99	1.42	4.36	0.326	18.60	7.42	0.31
	1988	3.31	1.26	5.19	0.244	16.14	8.63	0.31
	1996	3.64	1.24	6.13	0.203	14.04	7.95	0.25
	2002	4.13	1.21	7.17	0.169	12.22	7.63	0.21

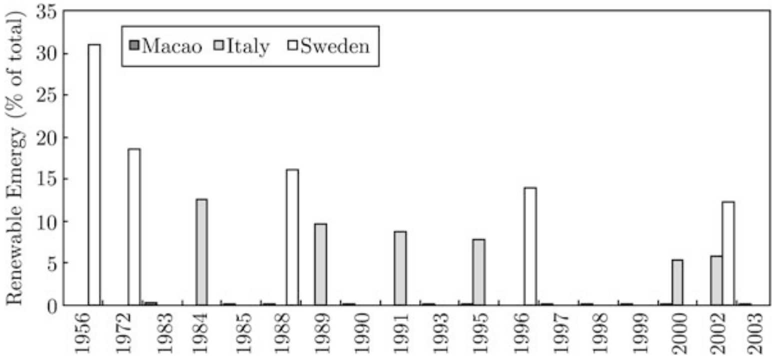

Fig. 2.22 Time series for the proportion of total emergy use in Macao of China, Italy, and Sweden accounted for by renewable emergy (%Ren) (Lei et al. 2012)

ment when the rate of development is greater than the rate of replenishment. These resources must therefore be carefully managed to avoid exceeding the natural environment's capacity to replenish them.

Unlike non-renewable resources such as fossil fuels, which cannot be replenished on human time scales, renewable resources have a sustainable yield if they are used wisely (Lei et al. 2012).

The value of %Ren differed greatly between the three regions (Table 2.7). Sweden is rich in natural resources, so its %Ren has been consistently higher than that of Italy (by more than 200 %), and was two orders of magnitude higher than that of Macao, which has few internal natural resources. These differences persisted throughout the study period (Fig. 2.22). However, %Ren has decreased over time for all three regions, since non-renewable fossil fuels have been the main energy source for modern society.

2.5.2 *Emergy Use Per Capita*

Figure 2.23 suggests that of the three regions, only Macao has shown a significant decrease in per capita emergy consumption during the study period, largely because of a shift to a non-industrial structure that is focused on the tourism sector. Macao nonetheless consumed more emergy per capita than Italy or Sweden throughout most of the study period.

2.5.3 *Emergy Money Ratio (E_m/\$)*

We found that E_m/\$ decreased throughout the study period (Fig. 2.24). Macao has had the highest E_m/\$ since about 1983, due to high NE as a result of inflows from tourism (Lei and Wang 2008a).

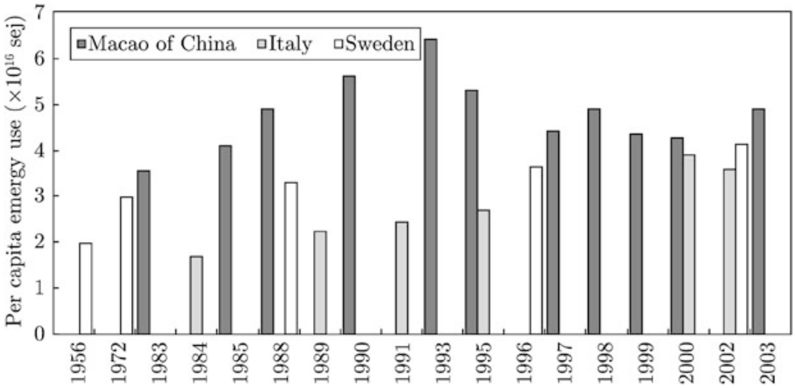

Fig. 2.23 Time series for the per capita emergy use for Macao of China, Italy, and Sweden

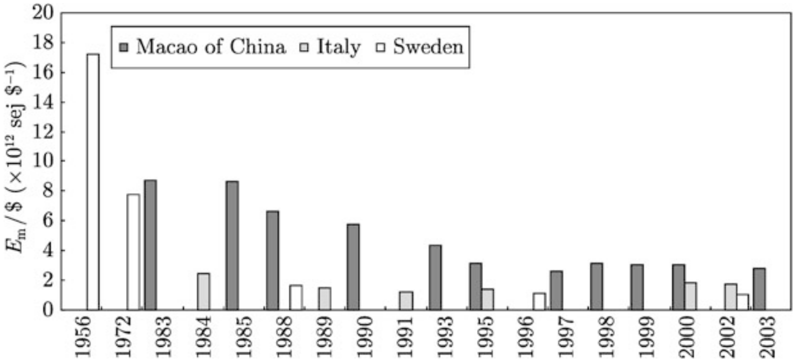

Fig. 2.24 Time series for the $E_m/\$$ for Macao of China, Italy, and Sweden

2.5.4 Integrated Emergy Index: The Environmental Sustainability Index (ESI)

The ESI of all three regions was considerably less than 1 throughout the study period (Table 2.7, Fig. 2.25), indicating that they are all highly developed consumer-oriented economies according to the criteria of Brown and Ulgiati (1997). In addition, ESI has declined throughout the study period for all three regions, as each economy depended on increasing flows of non-renewable emergy from outside the system, supported by increased imports of purchased energy and materials. Nonetheless, because ESI focuses mainly on the ecological aspects of a system, it has been criticized by economists as providing a weaker assessment of socioeconomic development than $E_m/\$$ (Hau and Bakshi 2004). Economists point out two shortcomings of ESI: First, ESI has declined rapidly in recent decades as economies have become increasingly dependent on flows of non-renewable emergy and on imports of purchased emergy and materials, thereby making the meaning of ESI unclear and

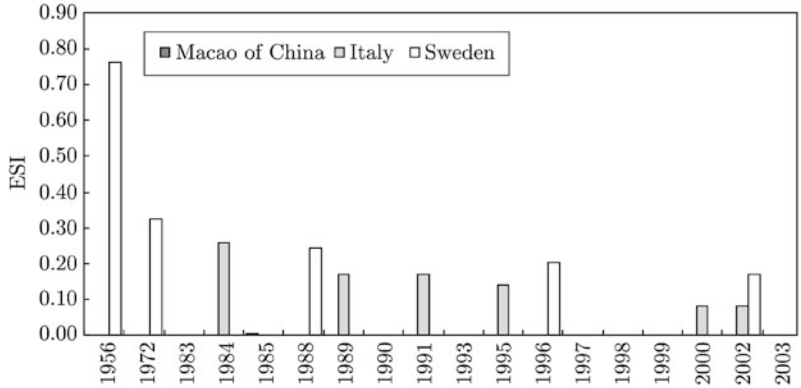

Fig. 2.25 Time series for the environmental sustainability index (ESI) for Macao of China, Italy, and Sweden (Lei et al. 2012)

implicit. Second, differences in scale between regions make it difficult to compare emergy flows between regions.

Figure 2.25 and Table 2.7 show that Macao's ESI is tiny compared with those of Italy and Sweden, and has declined starting in about 1983. This decline occurred because EYR remained steady while ELR increased (Lei et al. 2012). The ESI for Italy declined from 0.26 in 1984 to 0.08 in 2002. The ESI for Sweden's economy declined from 0.77 in 1956 to 0.17 in 2002.

At least two aspects of an analysis based on ESI must be improved to permit an adequate evaluation of a system's sustainable development: First, although all of a system's outputs are valuable from an ecological perspective in emergy accounting, we do not yet know how to make full use of these outputs. Thus, not all the system's outputs can be adequately valued in our analysis. Some are currently harmful and have negative impacts, such as waste and pollution, but this may change when improved technology lets us recover and reutilize these outputs. Because of limitations on current technology, not all systems with a high EYR are beneficial or promote sustainable development. Second, market prices of purchased inputs are influenced by many factors, such as market forces, cultural differences, ethical considerations, and the location of a system. Therefore, the same EYR value can have different consequences for a system because of differences in market factors (Lu et al. 2005). Third, the meaning of a specific ESI value is not clear; although a value closer to 1.0 is clearly more sustainable than a value closer to 0, the number alone does not tell us whether the system is sustainable in an absolute sense.

For these reasons, simplistic comparisons of ESI between systems can produce misleading results. At a national scale, ELR would be small when mostly renewable resources are used, but at a city scale, ELR is usually high due to large imports of renewable resources from outside the urban system, leading to a small ESI. However, for a region such as Sweden that is rich in natural resources, the imports of renewable emergy from outside a given city may be sustainable. Macao is a highly developed consumer-oriented economy with tremendous consumption of non-renewable

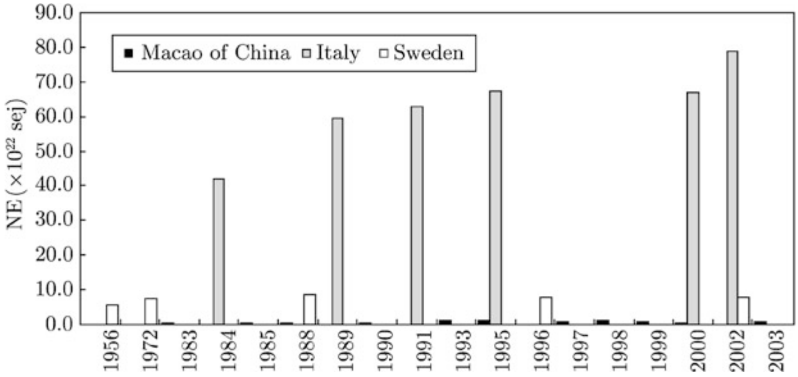

Fig. 2.26 Time series for the net emergy (NE) of Macao of China, Italy, and Sweden (Lei et al. 2012)

resources. These results show that ESI is an unsuitable index because of its limitations for describing the complexity of a system: it conceals too many differences between regions and between scales.

2.5.5 Storage Indices: NE and NER

The net emergy (NE) increased for all three regions during the study period (Fig. 2.26, Table 2.7). The NE was proportional to the population of each region (Table 2.7), so Macao's NE was much lower than those of Sweden and Italy. We found NE $>$ 0 for all three regions throughout the study period, which means that their emergy capital was sustainable based solely on a consideration of the results within each region's boundaries. This is a clearer result than the uncertain results of the ESI analysis.

NER appears to be the most reasonable measure of a system's sustainability in the long term. NER declined from 0.44 in 1982 to 0.28 in 2002 for Italy (Fig. 2.27, Table 2.7). For Macao, NER was 0.31 in 1983, increased to a peak of 0.47 in 1997, then oscillated until it returned to its original level (0.31) in 2003. The NER of Italy and Sweden has decreased in recent decades, though Italy's ELR has remained higher than Sweden's throughout the study period. Decreasing NER means that the accumulation of real emergy wealth is slowing. These results demonstrate that both ESI and NER have followed the same declining trend at a national scale, but that they sometimes followed a different pattern at different scales. The greater NER oscillation of Macao is to be expected, since small systems such as cities tend to oscillate more than large systems such as nations (H. T. Odum 1996).

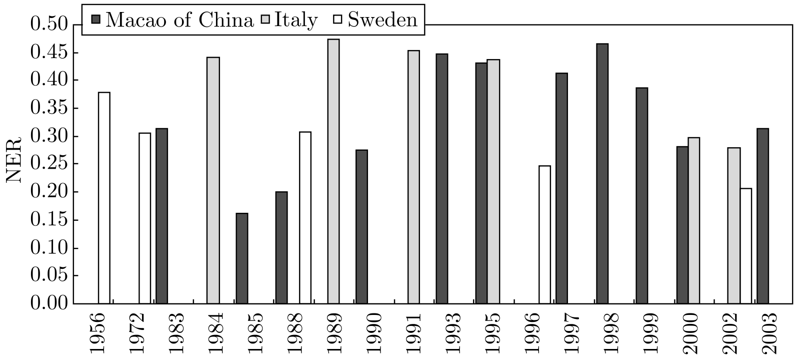

Fig. 2.27 Time series for the net emergy ratio (NER) of Macao of China, Italy, and Sweden (Lei et al. 2012)

2.6 Statistical Analyses of Emergy-Based Indicators of Macao

Table 2.8 shows the results of our correlation analysis between the various emergy statistics that we calculated. In summary:

Significant positive correlations: These combinations represented indicators that both increased over time. The following indicators were positively correlated with development processes: imported emergy, emergy used (U), exported emergy, emergy investment ratio (EIR), environmental loading ratio (ELR), per capita emergy used, per capita electricity emergy used, per capita fossil fuel used, and the ratio of electricity to U.

No significant correlation: The following indicators were not correlated with development processes: the ratio of renewable resources to emergy used, and the ratio of wastes to emergy used.

Significant negative correlations: These indicators represent indices that tend to decrease as development progresses. The following indicators were negatively correlated with development: the $E_m/\$$ ratio, the emergy yield ratio (EYR), ESI, and net emergy (NE).

2.7 Conclusions

Compared with mature ecosystems, limited urban ecosystems are relatively immature due to their rapid growth and inefficient use of resources. In addition, cities rely more strongly on ecosystems beyond the city limits than is the case for more self-contained natural ecosystems. As cities draw more and more resources from distant areas, they also accumulate large amounts of materials, including wastes discharged into the surrounding systems. Odum has observed that cities are among the most heterotrophic ecosystems in the biosphere, and this also appears to be true in all of the cities we studied (Macao, Zhongshan, Taipei, Miami-Dade County, and San Juan).

Table 2.8 The results of correlation analysis (Pearson's correlation coefficient) for the primary emergy components and indicators for Macao (Lei and Wang 2008a)

No.	Emergy-based indicators	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Imported emergy (F)															
2	Emergy used (U)	++														
3	Exported emergy (Y)	++	++													
4	Ratio of renewable resources (R) to U	0	0	0												
5	EIR	++	++	++	0											
6	ELR	++	++	++	0	++										
7	Ratio of wastes (W) to U	0	0	0	0	0	0									
8	Per capita emergy used	++	++	+	0	++	++	−								
9	Per capita electrical emergy	++	++	++	0	++	+	+	0							
10	Per capita fuel emergy	++	++	++	0	++	++	0	0	++						
11	E_m/$ ratio	−−	−−	−	0	−−	−−	0	0	−−	−−					
12	EYR	0	0	0	0	0	0	0	0	0	0	0				
13	Ratio of electricity emergy to U	0	0	+	0	−	0	++	0	++	++	−−	0			
14	ESI	−−	−−	−	0	−−	−−	0	−−	−	−	++	0	0		
15	NE	0	0	0	0	0	0	0	0	0	0	0	−−	0	−−	

Notes: −− and −, significant negative correlations at $P < 0.01$ and $P < 0.05$, respectively (two-tailed test). 0, no significant correlation. ++ and +, significant positive correlations at $P < 0.01$ and $P < 0.05$, respectively (two-tailed test)

From the point of view of systems ecology, cities are self-regulating systems and may be seen as super-organisms that were created for the benefit of human beings and for sustaining their livelihood.

Our research demonstrated that by relying on an imbalance between imports and exports, Macao has absorbed large amounts of emergy through inflows of negative entropy to support not only its survival, but also its booming development. EER has proven to be a useful indicator for studying emergy exchanges; an EER value of more than 1 means that the exchange brings an emergy surplus to the system, and this surplus can also be used in Macao's tourism industry. The imported emergy (F), emergy density, fuel and electricity emergy, and ELR of cities are much higher than those of natural systems. Dense cities usually have a very high ELR due to their lack of internal natural resources available for use. For a micro-ecosystem such as that of a small city, oscillations in emergy can always be found (H. T. Odum 1996); this variability reflects the instability and fragility of the system. Macao is now getting richer in emergy, but further studies will probably show that this has had a high environmental cost: local environmental resources have decreased greatly, and the need to import large quantities of emergy from surrounding regions may have had serious negative impacts on these regions.

We investigated the evolution of Macao's system from 1983 to 2004 by means of ecological energy accounting. Time-series analyses helped to reveal the dynamics of Macao's ecological economy. This approach can be applied to any country or region, provided that reliable data is available, and this highlights the importance of updating national analyses yearly to ensure the detection of long-term trends. An agreed-upon, standardized, and homogeneous procedure for emergy analysis is necessary to allow a reliable evaluation of a region's performance over time, as well as comparisons among different regions (e.g., using relevant emergy indicators such as ESI, NE, NER, ELR, and $E_{\mathrm{m}}/\$$). The comparison between Macao, Italy, and Sweden showed that emergy accounting significantly improves our understanding of the performance of a regional economy over time, and it reveals differences in the patterns for a given region.

We also employed correlation analysis to reveal that some of the emergy-based indicators that we used in the present study were positively and negatively correlated, whereas others showed no significant correlation.

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