Master's Thesis of Science in Agriculture

Emergy Analysis of Environmental Carrying Capacity for Sustainable Development Strategies of Resort Islands

에머지 분석을 통한 휴양섬의 환경용량 평가와 지속가능한 발전 방안 연구

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Emergy Analysis of Environmental Carrying Capacity for Sustainable Development Strategies of Resort Islands

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Abstract

The scale of resources consumed by the growing population has continually increased. Thus, interest in the environmental carrying capacity that can accommodate resource consumption and certain activities has also increased. A region can achieve sustainable development if there is future sustainability based on the economic and social activities that occur within the environmental carrying capacity. Since islands are isolated by the sea, they lack resources, and energy flow is difficult. Thus, the environmental carrying capacity of an island region is limited. In addition, resort islands have a large tourist population in addition to resident population, so it is necessary to assess the environmental carrying capacity of these islands by taking the tourist population into consideration.

There are many ways to evaluate the environmental carrying capacity including the ecological footprint, the Onishi model, and emergy analysis. A particularly useful approach is an emergy analysis, which calculates the environmental carrying capacity by considering the energy flow. Using this method reflects the characteristics of an island where inputs and outputs can be identified. From an energy perspective, this method can also assess the environmental load caused by the development of tourism.

Several studies on the evaluation of the environmental carrying capacity using an emergy analysis have been conducted. In South

Korea, the environmental carrying capacity has been assessed for each city. Analyzes have also been conducted overseas in areas such as China, Canada, Brazil, and Italy to evaluate sustainability. However, there are limits to using the findings of previous studies that have been conducted in mainland regions to reflect the characteristics of isolated island areas. Although some studies have considered tourism characteristics, there would be different results of the environmental carrying capacity in resort islands that have a higher tourist population and tourism influence.

The present study addresses this lack of research by evaluating the environmental carrying capacity of resort islands in 2015 using an emergy perspective. Chapter II discusses prior studies on this topic. Chapter III examines the characteristics of resort islands and the methodology to estimate the environmental carrying capacity. Chapter IV shows the results, and discusses the emergy evaluation, and compares the results of emergy and sustainability evaluations in three resort islands: Jeju Island, Hainan, and Hawaii. Finally, Chapter V summarizes the study results as a conclusion.

The key results of this study from 2015 are as follows. The imports emergy of Jeju Island accounted for 83% (1.75×10^{22} sej/year), while the rest comprised 11% of RE emergy (2.43×10^{21} sej/year), 5% of IR emergy (1.08×10^{21} sej/year), and 1% of EX emergy (1.76×10^{20} sej/year). The imports emergy of Hainan accounted for 52% (8.74×10^{22} sej/year), while the rest comprised 25% of IR emergy (4.22×10^{22} sej/year), 13% of EX emergy (2.18×10^{22} sej/year), and 10% of RE emergy (1.63×10^{22} sej/year). The imports emergy of Hawaii accounted for 71% (7.36×10^{22} sej/year), while the rest comprised 11% of IR emergy (1.10×10^{22} sej/year), 11% of RE emergy (1.08×10^{22} sej/year), and 7% of EX emergy (7.33×10^{21} sej/year).

Based on the evaluated emergy, the emergy indices (%Renew, EYR, ELR, SI, and CCP) were calculated and the sustainability of each region was evaluated. The %Renew (percent renewable) index was 0.73 (sustainable system) for Hawaii, 0.56 (transitional system) for Jeju Island, and 0.23 (unsustainable system) for Hainan. The EYR (emergy yield ratio) index was 3.98 (unsustainable system) for Hawaii, 2.27 (unsustainable system) for Jeju Island, and 1.30 (unsustainable system) for Hawaii. The ELR (environmental loading ratio) index was 0.36 (sustainable system) for Hawaii, 0.80 (sustainable system) for Jeju Island, and 3.35 (transitional system) for Hainan. The SI (sustainability index) was 11.02 (sustainable system) for Hawaii, 2.83 (transitional system) for Jeju Island, and 0.39 for Hainan. The CCP (carrying capacity of the population) was 1,530,000 for Hawaii, 780,000 for Jeju Island, and 12,170,000 for Hainan.

This study also proposes that the islands consider a premium tourism and a policy to utilize renewable energy. Premium tourism is expected to reduce the demand for imported emergy. Incorporating a renewable energy policy would reduce their reliance on external emergy sources. Theses policies will help improve the environmental carrying capacity of resort islands that have limited resources and must consider the tourist population.

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Chapter I. Introduction

1. Background

The environmental carrying capacity, which was developed from the broader capacity concept, refers to the ability of the environment to accommodate specific human activities (GESAMP, 1986; Han et al., 2011). The concept of environmental carrying capacity has various meanings in areas such as anthropology, regional development, and urban management. In particular, Catton interpreted the environmental carrying capacity as an "ecological" concept that can last without destroying the future sustainability of the environment (Catton, 1987). This requires the consumption of resources for economic and social activities of people within a range that does not impair their future sustainability to achieve sustainable development in the environment. Because of this relationship between the environment and sustainability, the environmental carrying capacity is commonly used to assess sustainable development in a region.

Islands provide a useful research material when analyzing sustainable development (Kerr, 2005). Islands, which are surrounded by the sea on four sides, are good sources to measure inputs and outputs for sustainable development because of their limited resources and isolated regional characteristics. Because islands tend to be geographically isolated from the mainland, their ecosystems are sensitive to changes not only from natural disasters but also global economic growth and global effects from climate change (Douglas, 2006). This environmental vulnerability could pose a threat to the natural ecosystems of islands, including energy flows (Kaly et al., 2002; Ghina, 2003). In addition to environmental vulnerability, a resort island, unlike a typical island, must also consider the impact of both tourists and the residents on the local environment. Resort islands such as Jeju Island, Hainan, and Hawaii represent islands where many tourists visit for entertainment and relaxation, and thus have a high proportion of the tourist population. The 2015 data on the proportion of the tourist population to resident population indicated that Jeju Island had 2145%, Hainan 586%, and Hawaii 598% tourist populations. Therefore, a study on sustainable development of resort islands needs to calculate the environmental carrying capacity considering the tourism population.

Methods for calculating the environmental carrying capacity include the ecological footprint, Onishi model, system dynamics, and emergy analysis. The ecological footprint assesses the environmental carrying capacity by converting the capacity needed to maintain economic activities into land area units (Wachernagle and Rees, 1996). The evaluation of the environmental carrying capacity through the ecological footprint index selects the resources required for economic activities and divides them into segments to calculate the land area per capita consumed for resource production. Then the environmental carrying capacity can be assessed by comparing the land area usage and the appropriate level in the area based on the calculated index.

The Onishi model estimates the environmental carrying capacity aimed at ensuring a certain standard of living for people within the environmental constraints. The model analyzes the demand and supply of facilities and services needed and determines whether there is an excess environmental carrying capacity in the region through a mismatch between demand and supply.

The next method, system dynamics, analyzes changes in the environmental carrying capacity through an analysis of complex causes and consequences. It also has the advantage of being able to analyze policy changes to improve the environmental carrying capacity because policy changes can be applied to the model.

Finally, the emergy analysis method analyzes the energy flow in the study areas to assess the environmental carrying capacity. It is considered an effective approach to assess the environmental load and sustainability inherent in energy, materials, and information invested in regional development (Odum, 1996; Pang et al., 2015).

The emergy analysis calculates the environmental carrying capacity based on the import and export of resources including energy resources. It is also possible to evaluate the environmental load and sustainable development due to the development of the tourism industry on the resort islands as an energy-centric system considering the development of renewable energy technologies.

Due to the advantages of emergy analysis, we chose to evaluate the environmental carrying capacity of resort islands using this method in this study. Numerous studies have estimated the environmental carrying capacity of various nations using an emergy analysis (Hossaini and Hewage, 2013; Chen et al., 2017; Zhang et al., 2017; Liu et al., 2018). Hossaini and Hewage (2013) evaluated emergy by analyzing the flow of energy, materials, and money in Canada and its provinces. Chen et al. (2017) measured the sustainability of Yunnan Province based on an emergy analysis, and proposed policies for sustainable development. However, most studies using emergy analysis have not been conducted in isolated island areas but in areas belonging to the mainland. Zhang et al. (2017) and Liu et al. (2018) also evaluated and presented the results on the sustainability of the Zengcheng region, taking into account all economic factors including tourism revenue as variables. However, the results of their emergy evaluations considering the tourists and tourism revenue were expected to differ from previous studies because resort islands are expected to have a higher tourism revenue than other areas.

2. Objectives

The purpose of this study was to evaluate the environmental carrying capacity using an emergy analysis and to propose policies for sustainable development based on three representative resort islands: Jeju Island, Hainan, and Hawaii. Three types of analyses were conducted:

(1) An emergy analysis method to calculate the emergy inherent in the energy, materials, and information of Jeju Island, Hainan, and Hawaii in 2015.

(2) Emergy indices to evaluate sustainability including the percent renewable (%Renew), emergy yield ratio (EYR), environmental loading ratio (ELR), sustainability index (SI), and carrying capacity of the population (CCP) for social and economic activities on Jeju Island, Hainan, and Hawaii.

(3) A comparative analysis to campare the emergy and sustainability results of Jeju Island, Hainan, and Hawaii.

Based on the results of these emergy evaluations, strategies are presented for sustainable development of resort islands.

Chapter II. Literature Review

1. Environmental Carrying Capacity

The environmental carrying capacity of regions have been studied since the early 20th century. It is translated as the maximum capacity of nature to retain its capabilities (Jung and Lee, 2009). Environmental carrying capacity is being used in a variety of areas, including regional development, urban development, and future sustainability assessments in both South Korea and abroad.

Brown et al. (1997) wanted to interpret the relationship between environmental carrying capacity and tourism development. Their study focused on the tourism industry from a sustainability perspective and its impact on the environmental load and natural resource degradation on the Maldives and Nepal. The results showed that the increased number of tourists in the Maldives and Nepal caused an increase in the environmental load. In particular, waste disposal was identified has been pointed out as an essential issue in both areas. They also concluded that both areas had exceeded their environmental carrying capacity. To address this environmental load problem, they recommended policies the development of the coral tourism in the Maldives and the development of new hiking routes in Nepal.

Jung and Lee (2009) analyzed the impact of urban residents' consumption behavior on the city’s environmental carrying capacity using the ecological footprint. Their results revealed that Daegu metropolitan area exceeded the environmental carrying capacity. To solve this problem, they recommended that Daegu establish an environmentally friendly land use plan considering the concept of sustainable development. In addition, they strongly recommended that the use of fossil fuels has to be reduced through alternative energy development.

Choi et al. (2011) also evaluated the environmental carrying capacity in Seoul metropolitan area using the ecological footprint in 1990, 2000, and 2009. They found that only Seoul and its surrounding cities showed excess environmental carrying capacity in 1990. However, by 2009, the environmental carrying capacity was exceeded not only in the Seoul area but also in cities outside the capital. Therefore, based on the calculated environmental carrying capacity results, they stressed that land development should be conducted in such a way that minimizes the environmental load and reduces the negative impact on the environment.

Widodo et al. (2015) analyzed the environmental carrying capacity of land and water resources for sustainable settlement development in the Yogyakarta urban area. Based on the results of their study, they estimated that the land resources would exceed the environmental carrying capacity by the year 2262, and the water resources would exceed environmental carrying capacity by the year 2161.

Zhang and Hao (2016) estimated the environmental carrying capacity by combining population capacity, land capacity, resource capacity and waste assimilative capacity in Hunan province in China and proposed several policies. The average environmental carrying capacity in 14 administration divisions in Hunan was 0.39, indicating that they have remained at the general condition level, ranging from 0.35 to 0.50. The waste assimilative capacity was analyzed as the most critical factor in the environmental carrying capacity system conducted in their study. In addition, the results of the Hunan's environmental carrying capacity was classified as the lower-middle level among the 30 provinces in China.

2. Emergy Analysis

The emergy analysis method is used to calculate the environmental carrying capacity. The environmental carrying capacity can be determined by estimating the local emergy index to estimate if sustainable development is feasible. Several researchers have used this method to determine the feasibility of an area. In addition, the relationship between the use of emergy and socio-economic development has helped policymakers formulate sustainable development strategies. For example, Hossaini and Hewage (2013) conducted an emergy analysis for Canada and its provinces. The results showed that the emergy yield ratio, one of the emergy indices, was good because Canada has abundant renewable energy and natural resources.

In contrast, Chen et al. (2017) conducted an emergy analysis for Yunnan Province and proposed a policy for the sustainable development of the region. Based on the results, he argued that Yunnan Province was not achieving sustainable development because it relies highly on local ecosystems. Thus, he proposed the introduction of a circular economy, the improvement of the industrial structure, and the development of renewable energy based on local resources as a policy to address the problems.

In Beijing, China, Qi et al. (2017) analyzed the urban metabolism using emergy analysis. Beijing was chosen because it has several counties, which allows policymakers to implement various policies. The study revealed that the emergy stores in Beijing from 2005 to 2014 steadily increased, especially in imports and exports emergy. They also found that the GDP growth and the increase of emergy in high urbanization areas had a strong correlation and that areas with low urbanization had the opposite effect.

In another city in China, Liu et al. (2018) analyzed the eco-efficiency change over the 2000-2016 period using the emergy analysis method in Zengcheng, a city in Guangzhou Province. They concluded that an increase in nonrenewable emergy weakens the natural ecosystem and the capacity for sustainable development.

3. Sustainable Development Strategies

The Brundtland Commission defined sustainable development as development that meets current requirements without sacrificing the ability to meet the needs of future generations (Brundtland Commission, 1987). Resort islands have excellent natural landscapes and tourism resources that have to be enjoyed by the current generation as well as the next generation. Therefore, resort islands should consider strategies for sustainable development.

Numerous researchers have studied sustainable resources and offered suggestions for long-term strategies. Lane (1994) defined sustainable tourism and studied whether there is a special relationship between sustainable tourism principles and the development of tourism. He argued that the relationship between the host areas and people, tourists, and the tourism industry should be balanced.

Muller (1994) also suggested ways for the local tourism industry to achieve sustainable development. He argued that economic health, optimum satisfaction of guest requirements, a healthy culture, subjective well-being, and unspoiled nature/protection of resources should be balanced. He also argued that we should reduce inequality, which wastes energy and human resources, and give the next generation the right to create their own world.

More recently, Kerr (2005) considered sustainable development of islands. He proposed measures to focus on economic growth such as replacement of imports, development of new export markets, and economic rent, as well as measures to develop human resources.

Chapter III. Materials and Methods

1. Resort Island

Resort islands are surrounded by water and are areas where tourists visit for entertainment and relaxation. In this study, we first examined the characteristics of resort islands to select islands to be used as study areas. We initially chose Hawaii, Jeju Island, Hainan, Guam, and Phuket as the most popular resort islands and Australia, New Zealand, Japan, Philippines, and Indonesia as representative island countries. Figure 1 shows the resident population and the tourist population on these resort islands and island countries. As shown in Figure 1, the resident population and tourist population of these resort islands, except Hainan, are smaller than those of the island countries. Resort islands also have a higher tourist population than the resident population, whereas island countries have a higher resident population than tourist population. Figure 2 shows the proportion of tourists (tourist population per resident population). The ratio of resort islands are all higher than 500%, while the island countries' population is less than 100%. As such, the resort islands have a lower resident population and higher tourist population than other (non-tourist) islands. These characteristics would affect the environmental carrying capacity of resort islands.

The area of each resort island is shown in Figure 3. In the five resort islands, Hainan has the largest area with 33,920 km^2 (SBHP, 2016), and Guam has the smallest area with 541 km^2 (Guam Bureau of Statistics and Plans, 2017). In this study, we calculated the environmental carrying capacity of resort islands and proposed sustainable development strategies. Thus, we decided that the resort islands should be given autonomy to suggest and implement policies in the region. Among the five resort islands, Jeju Island was elevated to a special self-governing province to develop into a special tourism zone in 2006, which guarantees a high level of autonomy (Kil, 2009). For the purposes of this study, it was decided that autonomy like Jeju Island should be guaranteed and the chosed islands should have a certain level of population and area for the sustainable policy to be implemented. After consideration of these characteristics for this study, Jeju Island, Hainan, and Hawaii were chosen as the main site of the research.

Jeju Island, Hainan, and Hawaii differ in tourism and region data. Figure 4 shows the 2015 tourism population, tourism revenue, resident population, and land area for the three regions. As for the tourism data, Hainan had the highest tourist population (53.6 million people) among the three regions (SBHP, 2016) and Hawaii had the highest tourism revenue of $15.1 billion (HTA, 2016). Jeju Island also had the highest population density and Hawaii had the lowest. The resident population and land area in decreasing order was Hainan, Hawaii, and Jeju Island.

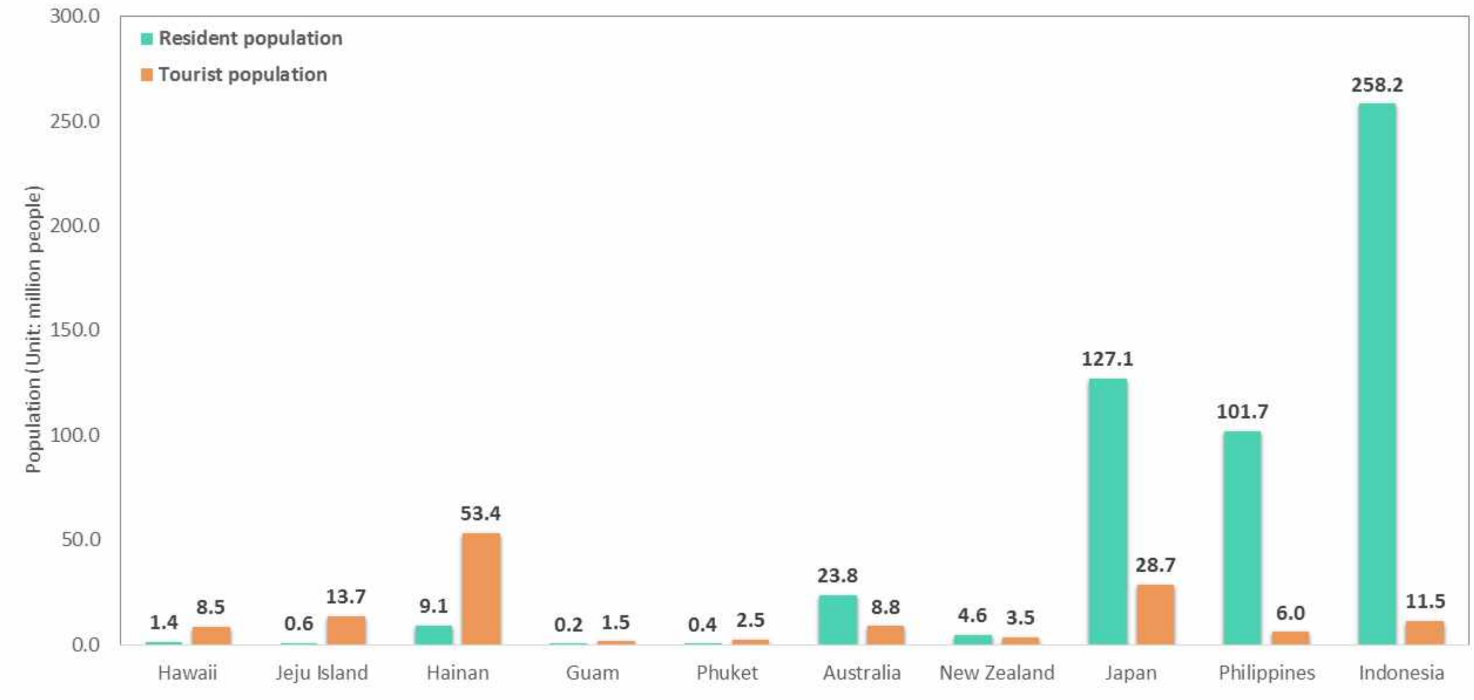


Figure 1 Resident and Tourist Population of Representative Islands in 2015

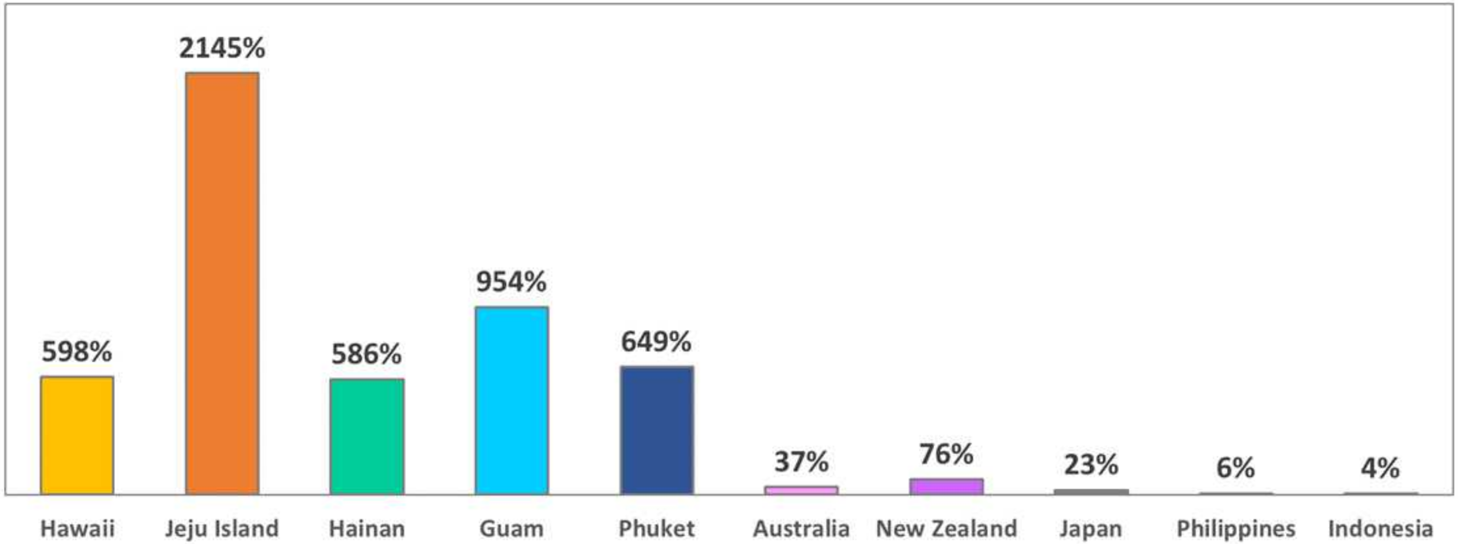


Figure 2 Tourist Population per Resident Population of Representative Islands in 2015

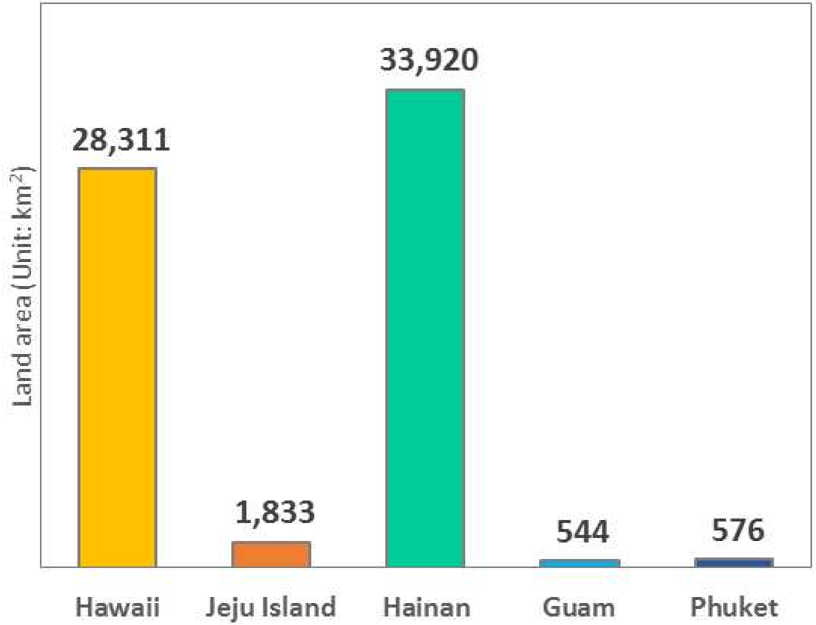


Figure 3 Land Area of the Resort Islands

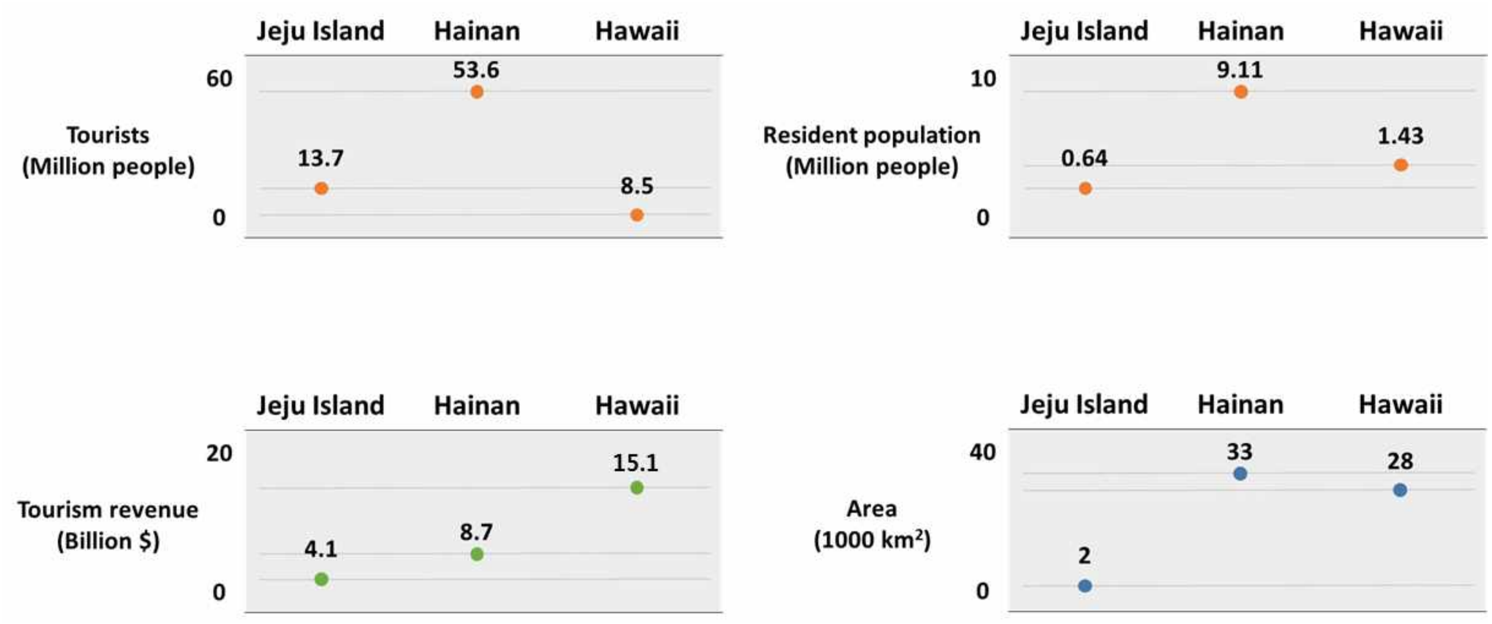


Figure 4 Information about Tourist and Region in Jeju Island, Hainan, and Hawaii

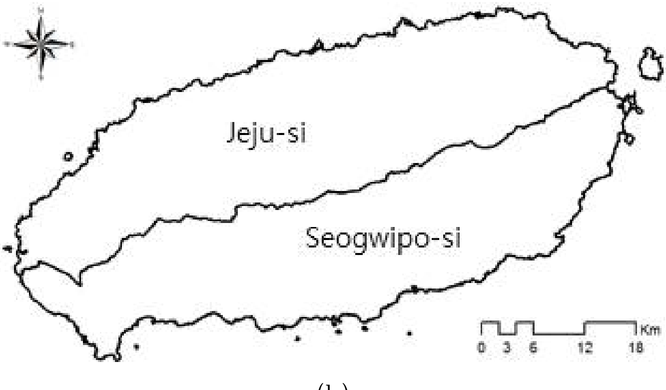
2. Study Area

2.1. Jeju Island

Jeju Island, the largest island in South Korea, is located in the southwestern part of the Korean peninsula with an area of 1833.2 km^2 (see Figure 5). The island's abundant tourism resources, such as its landscape and ecological diversity, led to the island being included as a bio-limited conservation area in 2002, was listed as a world natural heritage site in 2007, and was added as a new seven wonders of nature in 2011. Due to industrial development and the interest in tourism in Korea, roughly 14.75 million people traveled to Jeju Island in 2017.

The GDP of Jeju Island in 2015 was about 14,234 million dollars, the lowest among the study areas, but its GNP was the second highest at 22,345 dollars per capita (Jeju Special Self-Governing Province, 2016). The population grew from about 583,000 people in 2011 to about 641,000 people in 2015. The number of tourists increased by 56% from about 8.74 million people to about 13.66 million people during the same period (Jeju Special Self-Governing Province, 2016). The proportion of the tourism population (B/A in Figure 6) increased by 632%p from 1499% in 2011 to 2131% in 2015, the largest increase among the study areas. This indicates that the growth rate of the tourist population was higher than that of the resident population during the

(a)



(b)

Figure 5 (a) Location of South Korea relative to Jeju Island and (b) a Map of Jeju Island

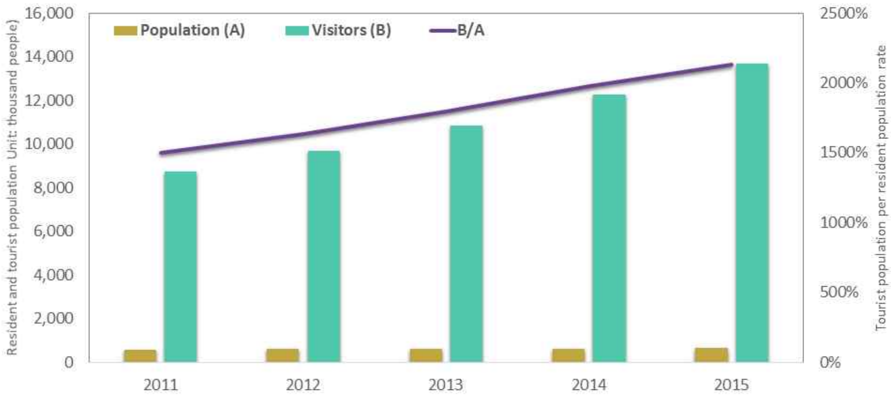


Figure 6 Resident and Tourist Population from 2011 to 2015 in Jeju Island

same period.

To determine the emergy of Jeju Island in 2015, the emergy of the RE category was calculated using the Jeju Statistical Yearbook (Jeju Special Self-Governing Province, 2016) and Annual Climatological Report (KMA, 2016). The emergy of the IR category was calculated using the Statistical Yearbook of Maritime Affairs and Fisheries (MOF, 2016) and the Statistical Yearbook of Food, Agriculture, Forestry, and Fisheries (MOF, 2016b). The emergy of the NR category was estimated using the Jeju Statistical Yearbook (Jeju Special Self-Governing Province, 2016). The emergy of the IM and EX categories was estimated using Korea International Trade Association (KITA, 2017) and Jeju Tourism Organization data (JTA, 2016) (see Table 1).

Table 1 Data Sources for Estimating Emergy of Jeju Island

Region	Item	Data sources
Jeju Island	Sun	▪ Jeju Statistical Yearbook (2016) ▪ Annual Climatological Report (2016)
	Wind	
	Rain	
	Wave	
	Fisheries production	▪ Statistical Yearbook of Maritime Affairs and Fisheries (2016) ▪ Statistical Yearbook of Food, Agriculture, Forestry, and Fisheries (2016)
	Water extraction	
	Forest extraction	
	Electricity use	▪ Yearbook of Regional Energy Statistics of Korea (2016)
	Topsoil losses	▪ Jeju Statistical Yearbook (2016)
	Fuels	▪ Korea International Trade Association (2017)
	Food & agricultural products	
	Livestock, meat, fish	
	Plastics & synthetic rubber	
	Chemicals	
	Finished products	
	Machinery & transp.equipments	
	Tourism	▪ Jeju Tourism Organization (2016)

2.2. Hainan

Hainan, one of China's southernmost administrative districts, is China's second largest island after Taiwan. Hainan has an area of 33,920 km^2 (SBHP, 2016), and the largest land area of China (see Figure 7).

The GDP of Hainan in 2015 was about 59,082 million dollars, the second highest among the study areas, but its GNP was the lowest at 6,485 dollars per capita (SBHP, 2016). The population grew from about 8.77 million in 2011 to about 9.11 million in 2015. The tourist rate increased by 78% from about 30 million to about 35 million during the

Figure 7 Location of Hainan in China

(Source: Wang and Wall, 2007)

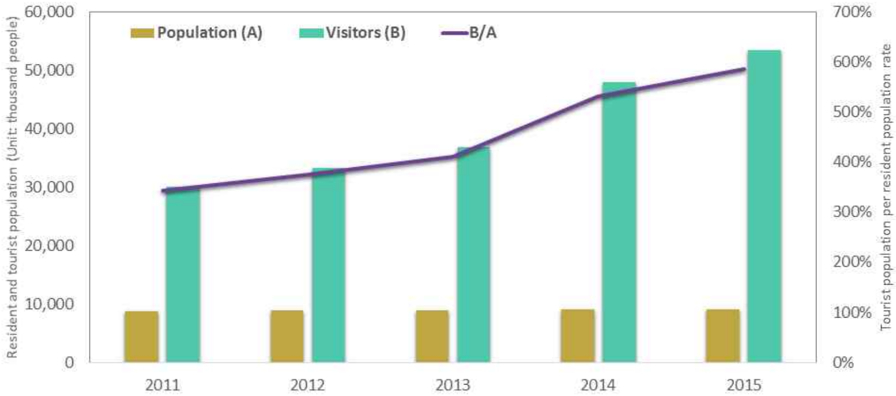


Figure 8 Resident and Tourist Population from 2011 to 2015 in Hainan

same period (SBHP, 2016). Hainan's tourist population in 2015 amounted to 362% of Jeju Island, as well as 617% of Hawaii (SBHP, 2016). The proportion of the tourism population (B/A in Figure 8) also increased, up 244%p from 342% in 2011 to 586% in 2015.

The emergy of Hainan in 2015 for the RE category was calculated using the Hainan Statistical Yearbook (SBHP, 2016) and Hainan Yearbook (The people's Government of Hainan Province, 2016). The emergy of the IR category was calculated using the Hainan Statistical Yearbook (2016, 2017) and the China National Statistical Office online data (National Bureau of Statistics of the People's Republic of China, 2016). The emergy of the NR category was estimated using the Hainan Statistical Yearbook (SBHP, 2016). The emergy the of IM and EX categories was estimated using the Hainan Statistical Yearbook (SBHP,

2016) (see Table 2).

Table 2 Data Sources for Estimating Emergy of Hainan

Region	Item	Data sources
Hainan	Sun	▪ Hainan Statistical Yearbook (2016) ▪ Hainan Yearbook (2016)
	Wind	
	Rain	
	Wave	
	Fisheries production	▪ Hainan Statistical Yearbook (2016) ▪ National Bureau of Statistics of the People's Republic of China (2016)
	Agricultural production	
	Water extraction	
	Forest extraction	
	Electricity use	▪ Hainan Statistical Yearbook (2017)
	Topsoil losses	▪ Hainan Statistical Yearbook (2016)
	Fuels	▪ Hainan Statistical Yearbook (2016)
	Food & agricultural products	
	Livestock, meat, fish	
	Chemicals	
	Tourism	▪ Hainan Statistical Yearbook (2016)

2.3. Hawaii

Hawaii is located in the eastern part of the North Pacific, and the capital city is Honolulu. Hawaii is the southernmost of the 50 states in the United States (see Figure 9). Hawaii has an area of 28,311 km^2 and a population of about 1.43 million by 2015 (DBEDT, 2016). Hawaii consists of Kauai County, Honolulu County, Kalawao County, Maui County, and Hawaii County. Hawaii, like Jeju Island, is a volcanic island and has abundant tourist resources such as Hawaii Volcanoes National Park, a UNESCO World Heritage site.

The GDP of Hawaii was 71.71 million dollars in 2015 and its GNP

Figure 9 Location of Hawaii

(Source: World Map)

Figure 10 Resident and Tourist Population from 2011 to 2015 in Hawaii

was 50,150 dollars per capita (DBEDT, 2016). These figures were the highest among the study areas of Jeju Island, Hainan and Hawaii. Hawaii's population grew 3% from about 1.38 million in 2011 to about 1.43 million in 2015. During the same period, the tourism population increased by 18% from about 7.3 million to about 8.65 million (HTA, 2016). Therefore, the proportion of tourism to resident population increased by 70%p from 530% in 2011 to 607% in 2015 (B/A in Figure 10). However, Hawaii had the lowest number of tourists compared to Jeju Island and Hainan.

The emergy of Hawaii in 2015 for the RE category was calculated using the state of Hawaii Data Book (DBEDT, 2016) and Hawaii Statewide GIS Program. The emergy of the IR category was calculated using the Fisheries of the United States (Van Voorhees et al., 2016), Crop Production 2015 summary (USDA and NASS, 2016), and the State of Hawaii Data Book (DBEDT, 2016). The emergy of the NR category was estimated using the State of Hawaii Data Book (DBEDT, 2016). The emergy of the IM and EX categories was estimated using the USA Trade Online (USCB, 2016) and Summary of 2016 Visitors to Hawaii (HTA, 2016) (see Table 3).

Table 3 Data Sources for Estimating Emergy of Hawaii

Region	Item	Data sources
Hawaii	Sun	▪ The State of Hawaii Data Book (2016) ▪ Hawaii Statewide GIS Program
	Wind	
	Rain	
	Wave	
	Fisheries production	▪ Fisheries of the United States (2016) ▪ Crop Production 2015 Summary ▪ The State of Hawaii Data Book (2016)
	Water extraction	
	Forest extraction	
	Electricity use	▪ The State of Hawaii Data Book (2016)
	Topsoil losses	▪ The State of Hawaii Data Book (2016)
	Fuels	▪ USA Trade Online (2016)
	Food & agricultural products	
	Livestock, meat, fish	
	Plastics & synthetic rubber	
	Chemicals	
	Finished products	
	Machinery & transp.equipments	
	Waste and scrap	
	Tourism	▪ Summary of 2016 Visitors to Hawaii (2016)

3. Environmental Carrying Capacity

3.1. Introduction

The environmental carrying capacity, which is developed from general capacity, is a social and scientific concept centered on human beings (Lee, 2001; Jeong, 2004; Lee et al., 2006). This concept can be defined as the size of the population and resources that can be accommodated. This environmental carrying capacity can be re-established according to the purpose of the calculation, can be used under certain conditions, and reflect time flow, space changes, and environmental carrying capacity needs. Thus, the definition and understanding of this concept vary based on different applications of the environmental carrying capacity concept (see Table 4).

Table 4 Definition of Environmental Carrying Capacity

Bioshop (1974)	The level of human activity that can permanently maintain an acceptable standard of living in a region.
Shelby and Heberlein (1986)	The level of use at which the impact exceeds the criteria set by the assessment criteria.
Catton (1987)	The size and strength of use that can be sustained without destroying the future sustainability of the environment for environmental use.
Odum (1989)	The number and biomass of life that a certain habitat can support.
Durham (1991)	The long-term capability of the natural environment to purify pollution and provide the necessary resources.

3.2. Evaluation Models

3.2.1. Ecological Footprint

The ecological footprint model is a tool to determine the environmental carrying capacity of a study area and the excess of the capacity required for human economic activities (Wackernagle and Rees, 1996). It measures the environmental carrying capacity by converting all the resources required for human economic activities into land areas. The resources required for economic activities mentioned in the ecological footprint model represent eight aspects: structure environment, energy production land, unproductive land, gardens, artificial forests, arable land, grass and natural forests. These resources are divided into four categories (i.e., food sector, structure environment sector, forestry sector, and energy sector) to calculate the environmental carrying capacity (see Figure 11). It is also possible to predict the future environmental carrying capacity by assessing the capacity of the study area as a method to calculate the land area used to sustain consumption of these resources (Hwang et al., 2006; Mclntyre and Emmi, 2007; Kang et al., 2014).

Using the ecological footprint index, the required land area for the consumption per capita in simple numbers can be analyzed. The results express the environmental carrying capacity as well as the sustainability of the area in broad terms. However, the limitations are that the ecological footprint index can not be used to present specific measures in the process of establishing a sustainable management system for a region.

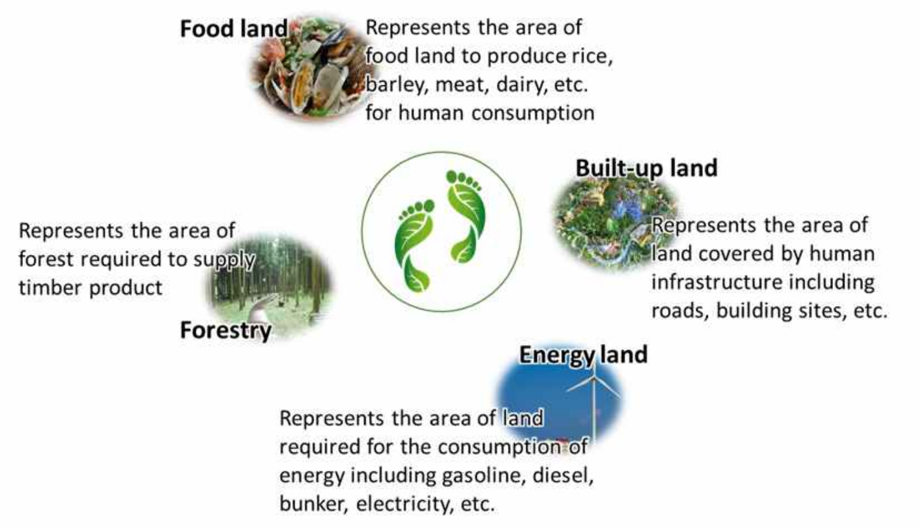


Figure 11 Concept Diagram of Ecological Footprint

3.2.2. Onishi Model

The Onishi model was developed as an approach to evaluate the environmental carrying capacity for sustainable development of Tokyo Metropolis (Hwang et al., 2006). This model evaluates the environmental carrying capacity based on areas such as water supply, sewage treatment, waste disposal, railways, roads, air pollution, and housing. The environmental carrying capacity using the Onishi model means finding a balance between the supply and demand for facilities and services that include selected areas (Lee, 2001) (see Figure 12). The Onishi model is based on the hypothesis of urban capacity limits. This hypothesis is that cities can not grow indefinitely, and that there are limitations to the size of the population and economic activities in which citizens can enjoy facilities and services.

The Onishi model has the advantage of assessing capacity through an analysis of supply and demand. However, since it is an assessment of the components of environmental carrying capacity, there are limitations as part of the assessment of environmental carrying capacity (Lee, 2001).

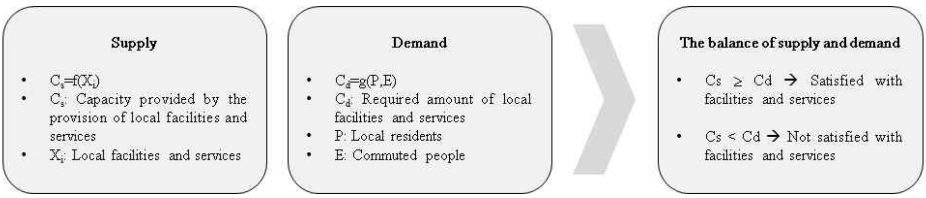


Figure 12 Concept of Onishi Model

3.2.3. System Dynamics Model

The system dynamics model is a method to identify the causes of complex problems and find solutions (Lee, 2001; Jang et al., 2013). It can show how a phenomenon with a complex causal relationship changes dynamically. Since human economic and social activities change through a combination of complex and cyclical interactions between components, a chain of causal relationships between components should be considered (Moon, 2007) (see Figure 13). Another advantage of the system dynamics model is its ability to identify the effectiveness of policies to improve the environmental carrying capacity within the model.

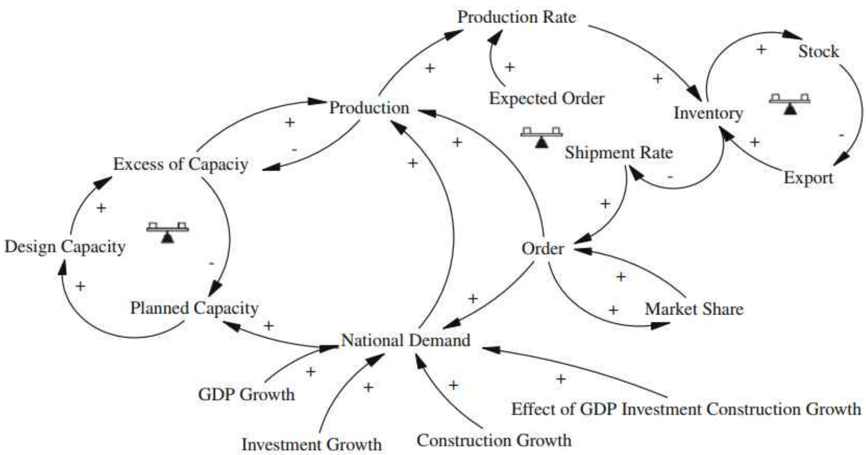


Figure 13 Concept Diagram of System Dynamics Model

(Source: Suryani et al., 2010)

4. Emergy Analysis

4.1. Introduction

An emergy analysis is defined as the sum of the available energy by converting all elements (energy, materials, and information) that serve as inputs into the direct and indirect production of a particular good or service (Odum, 1996). This method differs from an economic evaluation method, which determines the value of goods and services based on consumers' willingness to pay. The emergy analysis also includes a valuation of the production point that includes all factors that contribute to the production of goods and services (Kang, 2015).

Energy quality is also a characteristic of an emergy analysis (Odum, 1996). Different forms of energy cannot be compared simply by examining their different types, characteristics, and scales, but an emergy analysis allows for a comparison of the relative ability of each type of energy to show the overall flow of energy in a system. The unit energy value (UEV) is a factor that converts the difference in energy capability to the same comparable indicator. The UEV can be described as the amount of energy required to convert one type of energy into another. It can be divided into the energy conversion degree, the material conversion degree, and the emulsion ratio based on the object that must be converted (Kang, 2015). Solar energy is primarily used as an energy source in an emergy analysis. In this case, emergy can be referred to as solar emergy and UEV as solar transformity (Odum, 1996). It allows us to transfer the resource inputs (e.g., sun, agricultural production, topsoil losses, fuels) into solar emjoules (sej) (Asamoah et al., 2017). Solar emergy is a quantitative indicator that uses different types of energy units to represent the relative energy quality. The environmental carrying capacity is calculated by summing the total solar emergy required across all direct and indirect material and energy inputs used in the production of goods and services.

Emergy is composed of renewable energy (RE), nonrenewable source (NR) use from within a system, indigenous renewable energy (IR), imports (IM), and exports (EX). Emergy is calculated as:

$$EM_{SM} = \sum EM_{RE} + \sum EM_{NR} + \sum EM_{IR} + \sum EM_{IM} + \sum EM_{EX}$$

where EM_{SM} is the total of emergy consumed by a region or country in a year; EM_{RE} is the emergy of the RE category; EM_{NR} is the emergy of the NR category; EM_{IR} is the emergy of the IR category; EM_{IM} is the emergy of the IM category; and EM_{EX} is the emergy of the EX category.

To calculate the emergy of each category, the emergy of the items in the category are estimated as:

$$Emergy = Energy \times Solar\, transformity$$

The emergy (sej) of an item is estimated as the solar transformity (sej/J) and the energy (J) inherent in energy, materials, and information. This information comes from the flow of products or services required in people’s lives, and occurs when a product or service is moved and converted into energy.

4.2. Evaluation of the Environmental Carrying Capacity using an Emergy Analysis

To evaluate the environmental carrying capacity, items should be classified by category and emergy of each item should be calculated. Items classified by category are shown in Table 5. In the case of RE, emergy was calculated using the annual climatological reports and statistical data based on four items (sun, wind, rain, and wave).

The NR sector includes an item—soil organic matter loss—which is considered an unsustainable resource because of its slow regeneration (Kang, 2015).

The IR related to the economic activities of Jeju Island is the emergy based on renewable energy. The items of the IR category were selected by considering the resource depletion caused by the development of the tourism industry. Four items were chosen to reflect the decline of agricultural products, the decrease of fishery products caused by overfishing, the depletion of water resources due to population growth, and the reduction of forest extraction from tourism resource development.

The nine and eight items were evaluated from the IM and EX categories, respectively. Among the items of the IM category, the electricity use item was added as an indicator of the regional characteristics of Jeju Island. Unlike other regions, Jeju Island sources its electricity through HVDC with the mainland rather than through power generation in order to preserve the clean, natural environment and because of the difficulty of providing fuel. Thus, the lack of electricity was supplied by HVDC from the South Korean mainland, largely coming from Haenam and Jindo of Jeon-nam, at 39% (Jeju Special Self-Governing Province, 2016). Although the electricity use item is generally assigned to the IR category, it was added to the IM category in this study because it was considered a characteristic of Jeju Island. In the case of Hainan, statistics show that there were no import data for plastics and synthetic rubber finished products, and machinery and transportation equipment in 2015, and no export data for livestock,

Table 5 Categories and Items for Emergy Evaluation

Category	Item
Renewable Resources (RE)	sun, wind, rain (chemical potential), wave
Indigenous Renewable Energy (IR)	fisheries production, agricultural production, water extraction, electricity use, forest extraction
Nonrenewable Source use from Within System (NR)	topsoil losses
Imports (IM)	fuels, food & agricultural products, livestock & meat&fish, plastics & synthetic rubber, chemicals, finished products, machinery&transportation equipments, electricity, tourism
Exports (EX)	fuels, waste and scrap, food & agricultural products, livestock & meat & fish, plastics & synthetic rubber, chemicals, finished products, machinery & transportation equipments

meat, fish, plastics and synthetic rubber, finished products, and machinery and transportation equipment. In the items of the EX category, fuel is the export item that exists only in Hainan. Since Jeju Island and Hawaii only import fuel, we do not calculate the emergy of fuel exports. For Hawaii, the waste and scrap item is only a characteristic of Hawaii.

4.3. Emergy Indices

Emergy indices are used to evaluate an energy flow system and to understand the sustainability of development. Emergy indices include the percent renewable (%Renew), emergy yield ratio (EYR), environmental loading ratio (ELR), sustainability index (SI), and carrying capacity of the population (CCP). Detailed estimation equations are as follows:

$$\%Renew = \frac{R}{R+N+F}$$

$$EYR = \frac{R+N+F}{F}$$

$$ELR = \frac{N+F}{R}$$

$$SI = \frac{EYR}{ELR}$$

$$CCP = 8 \times \frac{R}{U} \times population$$

$$U = R+N+F+P2L$$

where R is a permanent emergy (which is the same as the emergy of RE shown in Table 5, R); N is nonpermanent emergy (the same as the emergy of NR in Table 5, N); F is nonpermanent purchased emergy (the emergy of IM in Table 5 except tourism, F); and P2L is the used goods and services emergy (the same as the emergy of tourism in Table 5, P2L) (Brown and McClanahan, 1996).

%Renew represents the ratio of renewable emergy from the total emergy. This index is a key factor in determining the sustainable development potential when considering the long-term development of a country or region. EYR is defined as the ratio of the emergy (R + N + F) flowing into an area divided by the nonpermanent purchased emergy. This index is an indicator of the efficiency and productivity of regional systems. ELR represents the degree of the environmental load on the local ecosystem. This is also mainly used as an indicator of the impact of human economic and social activities on the surrounding environment. SI represents the degree of sustainability of the system based on current environmental conditions and economic activities. CCP is an indicator of the extent to which social and economic activities are sustainable. This is calculated using the ratio of permanent emergy and used emergy (R + N + F + P2L), the population, and the value 8, which represents the level of economic development in developed countries to determine whether human economic and social activities are within the capacity of the ecosystem (Brown and McClanahan, 1996).

Each index can be divided into an unsustainable system, transitional system, and sustainable system. It can be used to assess the environmental carrying capacity and sustainability of the region. The ranges of indices corresponding to the system are shown in Figure 14.

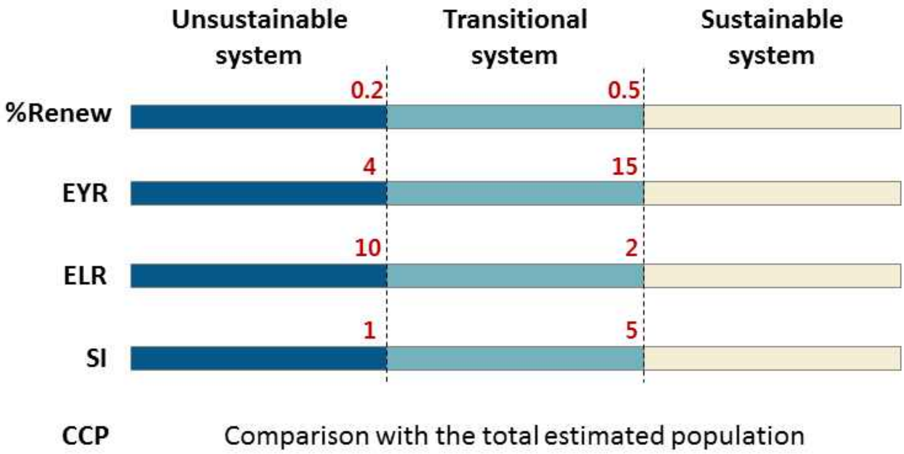


Figure 14 Ranges of Emergy Indices corresponding to the System

Chapter IV. Results and Discussion

1. Emergy Evaluations of Study Areas

1.1. Emergy of Jeju Island

The emergy of Jeju Island, based on the energy of the category items in 2015, was evaluated as shown in Table 6. In this study, the base energy was set as the solar energy to compare the energy of different resources. The total emergy of Jeju Island was 2.79×10^{22} sej/year in 2015.

The emergy of each category was estimated as RE 2.43×10^{21} sej/year, IR 1.08×10^{21} sej/year, NR 1.98×10^{19} sej/year, IM 1.75×10^{22} sej/year, and EX 1.76×10^{20} sej/year.

The emergy in RE refers to the amount of emergy in the wave item which was calculated using the length of the coastline and the wave energy density of Jeju Island. Each item is closely related because renewable energy is basically powered by solar energy. Therefore, duplicate calculation errors can occur (Kim and Chang, 2016). The emergy of RE was selected as the item with the highest amount of emergy (Zuo et al., 2004; Yang et al., 2017). The sun item represents the renewable energy source that provided the largest amount of energy (1.33×10^{19} J/year) needed for Jeju Island in 2015. This amount corresponded to about 279 times the energy of the wave item; however, after examining the contribution of emergy, it was found that the contribution of the rain, wind, and sun items was less than the contribution of the wave item, which had the highest emergy in RE (2.43×10^{21} sej/year). Therefore, if simple comparisons are made without considering the difference between the different types of energy, the value of the actual energy contribution to the region cannot be evaluated properly (Kim and Chang, 2016).

In the case of IR, the emergy of the electricity use item, which accounted for about 81% of IR on Jeju Island, showed the highest value (8.76×10^{20} sej/year). This is related to the tourism industry. Tourism is an important industry related to power consumption (Kim et al., 2015). As one of the most popular tourist destinations in South Korea, Jeju Island continued to develop its tourism resources, which increased the demand for tourism on the island. To meet this tourism demand, Jeju Island has increased tourism facilities and is believed to have increased its electricity consumption. In particular, Jeju Island has electricity-related emergy in the IM category as well as IR category. Therefore, it is expected that the electricity item will have a significant effect on the assessment of emergy evaluation in Jeju Island. The emergy contribution for IR showed a decreasing order from the water extraction (1.84×10^{20} sej/year) to the fisheries production item (7.12×10^{14} sej/year). For NR (1.98×10^{19} sej/year), only the topsoil losses item was calculated. This category accounted for 0.01% of total emergy, which was the smallest portion.

The emergy of IM, which accounted for the largest share of total emergy, was 1.75×10^{22} sej/year and was estimated to account for about 88% of total emergy (see Figure 15). The emergy of the tourism item accounted for 89% (1.56×10^{22} sej/year) of IM, which was the highest contribution. The contribution showed a decreasing order from the livestock, meat, fish item (8.67×10^{20} sej/year) to the electricity use item (4.93×10^{20} sej/year). In addition to the IR category, the emergy of electricity item was calculated in the IM category. Jeju Island, unlike Hainan and Hawaii, is a region where electricity can be supplied using HVDC because the distance between Jeju Island and the mainland is relatively close. Therefore, we selected electricity as an item of the IM category and analyzed how much electricity imported would affect the sustainability of Jeju Island.

The energy (revenue) generated by the tourism item was 4.10×10^{19} \$/year, the third lowest in IM; however, it was estimated that the emergy of the tourism item was the highest among the items because it

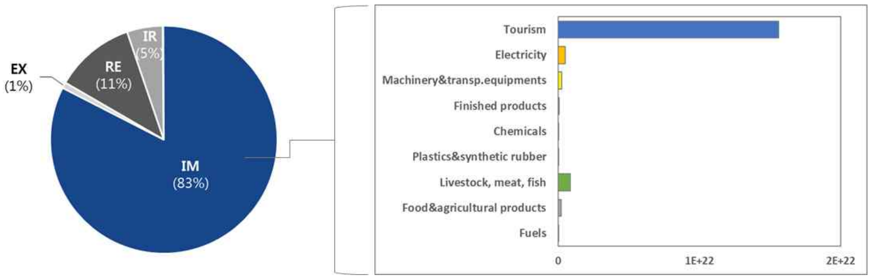


Figure 15 Emergy Results of Imports Category by Items in Jeju Island

had the highest UEV (3.81×10^{12}). This means that tourism revenue would be accompanied by considerable energy, and it was determined that it would have a significant impact on the results of emergy evaluation.

For EX, the livestock, meat, fish item had an emergy volume of 1.25×10^{20} sej/year, which accounted for about 71% of EX. The contribution decreased in the order of the plastics and synthetic rubber item (1.54×10^{19} sej/year) and the machinery and transportation equipment item (1.30×10^{19} sej/year).

Table 6 Emergy Evaluation of Jeju Island in 2015

No.	Item	Flow	Unit	UEV	UEV source[a)]	Emergy(sej/yr)(%[c)])
Renewable energy						
1	Sun	1.33E+19	J/yr	1	1	1.33E+19
2	Wind	1.55E+16	J/yr	2.45E+03	1	3.80E+19
3	Rain, chemical potential	1.93E+16	J/yr	3.05E+04	1	5.89E+20
4	Wave	4.76E+16	J/yr	5.10E+04	1	2.43E+21
max[b)]						2.43E+21
Indigenous renewable energy						
5	Fisheries production	2.12E+08	J/yr	3.36E+06	2	7.12E+14 (0%)
6	Agricultural production	8.99E+09	J/yr	3.36E+05	2	3.02E+15 (0%)
7	Water extraction	7.69E+14	J/yr	varies	1, 3	1.84E+20 (17%)
8	Electricity use	3.06E+15	J/yr	2.86E+05	4	8.76E+20 (81%)
9	Forest extraction	9.82E+14	J/yr	2.21E+04	5	2.17E+19 (2%)
sum						1.08E+21
Nonrenewable sources from within system						
10	Topsoil losses	1.61E+15	J/yr	1.23E+04	6	1.98E+19 (100%)
sum						1.98E+19
Imports						
11	Fuels	1.62E+13	J/yr	8.36E+04	7	1.35E+18 (0.01%)
12	Food&agricultural products	1.41E+15	J/yr	1.52E+05	8	2.14E+20 (1%)
13	Livestock, meat, fish	3.02E+14	J/yr	2.87E+06	8	8.67E+20 (5%)
14	Plastics&synthetic rubber	1.31E+07	g/yr	1.40E+10	8	1.84E+17 (0.001%)
15	Chemicals	3.30E+09	mixed	4.20E+09	8	1.39E+19 (0.1%)
16	Finished products	1.81E+10	mixed	3.89E+09	8	7.03E+19 (0.4%)
17	Machinery&transp.equipments	1.19E+10	g/yr	2.22E+10	8	2.65E+20 (2%)
18	Electricity	1.72E+15	J/yr	2.86E+05	4	4.93E+20 (3%)
19	Tourism	4.10E+09	$/yr	3.81E+12	9	1.56E+22 (89%)
sum						1.75E+22
Exports						
20	Food&agricultural products	8.56E+13	J/yr	1.31E+05	8	1.12E+19 (6%)
21	Livestock, meat, fish	1.44E+13	J/yr	8.71E+06	8	1.25E+20 (71%)
22	Plastics&synthetic rubber	1.20E+09	g/yr	1.29E+10	8	1.54E+19 (9%)
23	Chemicals	7.50E+07	mixed	4.71E+09	8	3.53E+17 (0.2%)
24	Finished products	1.38E+09	mixed	7.75E+09	8	1.07E+19 (6%)
25	Machinery&transp.equipments	5.87E+08	g/yr	2.22E+10	8	1.30E+19 (7%)
sum						1.76E+20

a) UEV sources: 1) Odum et al.(2000), 2) Brown and McClanahan (1996), 3) Buenfil (2001), 4) Odum (1996), 5) Romitelli (2000), 6) Brown and Ulgiati (2011), 7) Liu et al (2011)., 8) Cohen et al (2007)., 9) Ascione et al (2009)

b) The sum of the renewable resources is determined by the largest value among the items to avoid the duplicate calculation.

c) These percentages show the portion in each category. In the category of renewable energy, there is no portion due to using with the maximum of emergy of the renewable energy category.

1.2. Emergy of Hainan

The emergy of Hainan, based on the energy of the category items in 2015, was evaluated as shown in Table 7. The emergy of each category was estimated as RE 1.63×10^{22} sej/year, IR 4.22×10^{22} sej/year, NR 1.53×10^{20} sej/year, IM 8.74×10^{22} sej/year, and EX 2.17×10^{22} sej/year.

The emergy in RE refers to the amount of emergy in the wave item and was calculated to 1.63×10^{22} sej/year. In the case of IR, the emergy of the electricity use item, which accounted for about 67% of IR, showed the highest value (2.80×10^{22} sej/year). The emergy contribution for IR showed a decreasing order from the water extraction (1.40×10^{22} sej/year) to the agricultural production item (6.53×10^{16} sej/year). For NR, the topsoil losses item was calculated to 1.53×10^{20} sej/year. This category accounted for 0.01% of total emergy, which was the smallest portion.

In the IM category, the emergy of the fuels item accounted for 62% (5.44×10^{22} sej/year) of IM, which was the highest contribution (see Figure 16). The contribution showed a decreasing order from the tourism item (3.29×10^{22} sej/year) to the food and agricultural products item (1.98×10^{15} sej/year).

For EX, the fuels item had an emergy volume of 1.84×10^{22} sej/year, which accounted for about 85% of EX. The contribution decreased in the order of the chemicals item (3.35×10^{21} sej/year) to the food and agricultural products item (1.17×10^{15} sej/year).

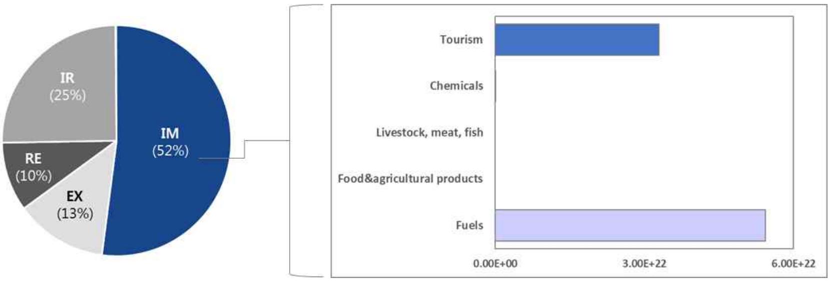


Figure 16 Emergy Results of Imports Category by Items in Hainan

Table 7 Emergy Evaluation of Hainan in 2015

No.	Item	Flow	Unit	UEV	UEV source[a)]	Emergy(sej/yr)(%[c)])
Renewable energy						
1	Sun	1.47E+22	J/yr	1	1	1.47E+22
2	Wind	2.50E+17	J/yr	2.45E+03	1	6.11E+20
3	Rain, chemical potential	2.86E+17	J/yr	3.05E+04	1	8.73E+21
4	Wave	3.20E+17	J/yr	5.10E+04	1	1.63E+22
max[b)]						1.47E+26
Indigenous renewable energy						
5	Fisheries production	8.67E+09	J/yr	3.36E+06	2	2.91E+16 (0%)
6	Agricultural production	1.94E+11	J/yr	3.36E+05	2	6.53E+16 (0%)
7	Water extraction	1.21E+17	J/yr	varies	1, 3	1.40E+22 (33%)
8	Electricity use	9.80.E+16	J/yr	2.86E+05	4	2.80E+22 (67%)
9	Forest extraction	6.45E+15	J/yr	2.21E+04	5	1.43E+20 (0.3%)
sum						4.22E+22
Nonrenewable sources from within system						
10	Topsoil losses	1.24E+16	J/yr	1.23E+04	6	1.53E+20 (100%)
sum						1.53E+20
Imports						
11	Fuels	6.51.E+17	J/yr	8.36E+04	7	5.44E+22 (62%)
12	Food&agricultural products	1.30.E+10	J/yr	1.52E+05	8	1.98E+15 (0%)
13	Livestock, meat, fish	2.44.E+05	J/yr	2.87E+06	8	7.00E+11 (0%)
14	Chemicals	1.23.E+10	mixed	4.20E+09	8	5.16E+19 (0.1%)
15	Tourism	8.65.E+09	$/yr	3.81E+12	9	3.29E+22 (38%)
sum						8.74E+22
Exports						
16	Fuels	1.37.E+17	g/yr	2.16E+09	8	1.84E+22 (85%)
17	Food&agricultural products	8.91.E+09	J/yr	1.31E+05	8	1.17E+15 (0%)
18	Chemicals	7.11.E+11	mixed	4.71E+09	8	3.35E+21 (15%)
sum						

a) UEV sources: 1) Odum et al.(2000), 2) Brown and McClanahan (1996), 3) Buenfil (2001), 4) Odum (1996), 5) Romitelli (2000), 6) Brown and Ulgiati (2011), 7) Liu et al (2011)., 8) Cohen et al (2007)., 9) Ascione et al (2009)

b) The sum of the renewable resources is determined by the largest value among the items to avoid the duplicate calculation.

c) These percentages show the portion in each category. In the category of renewable energy, there is no portion due to using with the maximum of emergy of the renewable energy category.

1.3. Emergy of Hawaii

The emergy of Hawaii, based on the energy of the category items in 2015, was evaluated as shown in Table 8. The emergy of each category for Hawaii was estimated as RE 1.08×10^{22} sej/year, IR 1.10×10^{22} sej/year, NR 1.98×10^{20} sej/year, IM 5.99×10^{22} sej/year, and EX 7.33×10^{22} sej/year. The emergy of RE refers to the amount of emergy in the wave item and was calculated to 1.08×10^{22} sej/year.

In the case of IR, the emergy of the electricity use item, which accounted for about 88% of IR, showed the highest value (9.67×10^{21} sej/year). The emergy contribution for IR showed a decreasing order from the water extraction (1.23×10^{21} sej/year) to the fisheries production item (2.21×10^{14} sej/year). For NR, the topsoil losses item was calculated to 1.98×10^{20} sej/year. This category accounted for 0.01% of total emergy, which was the smallest portion.

In the IM category, the emergy of the tourism item accounted for 81% (5.94×10^{22} sej/year) of IM, which was the highest contribution (see Figure 17). The contribution showed a decreasing order from the food and agricultural products item (1.16×10^{22} sej/year) to the chemicals item (1.17×10^{19} sej/year).

For EX, the finished products item had an emergy volume of 6.01×10^{21} sej/year, which accounted for about 82% of EX. The contribution decreased in the order of the livestock, meat, fish item (4.53×10^{20} sej/year) to the plastics and synthetic rubber item (2.17×10^{19} sej/year).

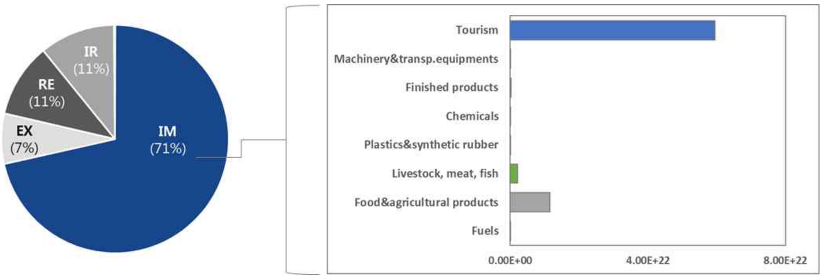


Figure 17 Emergy Results of Imports Category by Items in Hawaii

In Hawaii, the EX category includes a waste and scrap item because Hawaii exports items to other countries that are not worth using. The waste and scrap item is not considered a factor that will hinder Hawaii’s environmental carrying capacity and sustainable development because the export category does not affect the results of the emergy index calculation. However, the IM category can affect the local environmental carrying capacity and sustainable development. Thus, the waste and scrap exports of Hawaii represent imports from other regions, which may undermine sustainable development in the region.

Table 8 Emergy Evaluation of Hawaii in 2015

No.	Item	Flow	Unit	UEV	UEV source[a)]	Emergy(sej/yr)(%[c)])
Renewable energy						
1	Sun	1.15E+20	J/yr	1	1	1.15E+20
2	Wind	1.55E+16	J/yr	2.45E+03	1	9.22E+18
3	Rain, chemical potential	1.93E+16	J/yr	3.05E+04	1	3.16E+21
4	Wave	4.76E+16	J/yr	5.10E+04	1	1.08E+22
max[b)]						1.08E+22
Indigenous renewable energy						
5	Fisheries production	6.57E+07	J/yr	3.36E+06	2	2.21E+14 (0%)
6	Agricultural production	1.97E+10	J/yr	3.36E+05	2	6.61E+15 (0%)
7	Water extraction	8.67E+15	J/yr	varies	1, 3	1.23E+21 (11%)
8	Electricity use	3.38E+16	J/yr	2.86E+05	4	9.67E+21 (88%)
9	Forest extraction	6.01E+15	J/yr	2.21E+04	5	1.33E+20 (1%)
sum						1.10E+22
Nonrenewable sources from within system						
10	Topsoil losses	1.61E+16	J/yr	1.23E+04	6	1.98E+20 (100%)
sum						1.98E+20
Imports						
11	Fuels	5.13E+14	J/yr	8.36E+04	7	4.29E+19 (0.1%)
12	Food&agricultural products	7.61E+16	J/yr	1.52E+05	8	1.16E+22 (16%)
13	Livestock, meat, fish	7.32E+14	J/yr	2.87E+06	8	2.10E+21 (3%)
14	Plastics&synthetic rubber	1.18E+10	g/yr	1.40E+10	8	1.65E+20 (0.2%)
15	Chemicals	2.79E+09	mixed	4.20E+09	8	1.17E+19 (0.02%)
16	Finished products	5.33E+10	mixed	3.89E+09	8	2.07E+20 (0.3%)
17	Machinery&transp.equipments	9.24E+08	g/yr	2.22E+10	8	2.05E+19 (0.03%)
18	Tourism	1.56E+10	$/yr	3.81E+12	9	5.94E+22 (81%)
sum						7.36E+22
Exports						
19	Waste and scrap	1.83E+11	g/yr	2.16E+09	10	3.95E+20 (5%)
20	Food&agricultural products	9.13E+14	J/yr	1.31E+05	8	1.20E+20 (2%)
21	Livestock, meat, fish	5.21E+13	J/yr	8.71E+06	8	4.53E+20 (6%)
22	Plastics&synthetic rubber	1.68E+09	g/yr	1.29E+10	8	2.17E+19 (0.3%)
23	Chemicals	5.31E+10	mixed	4.71E+09	8	2.50E+20 (3%)
24	Finished products	7.75E+11	mixed	7.75E+09	8	6.01E+21 (82%)
25	Machinery&transp.equipments	3.65E+09	g/yr	2.22E+10	8	8.11E+19 (1%)
sum						7.33E+21

a) UEV sources: 1) Odum et al.(2000), 2) Brown and McClanahan (1996), 3) Buenfil (2001), 4) Odum (1996), 5) Romitelli (2000), 6) Brown and Ulgiati (2011), 7) Liu et al. (2011), 8) Cohen et al. (2007), 9) Ascione et al. (2009), 10) Buranakarn (1998)

b) The sum of the renewable resources is determined by the largest value among the items to avoid the duplicate calculation.

c) These percentages show the portion in each category. In the category of renewable energy, there is no portion due to using with the maximum of emergy of the renewable energy category.

2. Sustainability Evaluations of Study Areas

2.1. Sustainability of Jeju Island

The environmental carrying capacity for the sustainable development of Jeju Island was evaluated based on the estimated emergy indices, including the percent renewable (%Renew), emergy yield ratio (EYR), environmental loading ratio (ELR), sustainability index (SI), and carrying capacity of the population (CCP). These indices should be compared across indicators. The results of the indices were grouped into three types of systems: a sustainable system, transitional system, and unsustainable system.

The variables needed to calculate the emergy index on Jeju Island were calculated as R for 2.43×10^{21} sej/year, N for 1.98×10^{19} sej/year, F for 1.92×10^{21} sej/year, and P2L for 1.75×10^{22} sej/year.

The results of Jeju Island's emergy indices for 2015 are shown in Figure 18. %Renew was calculated at 0.56, indicating a sustainable system. EYR was estimated at 2.27, indicating an unsustainable system. ELR was 0.80, indicating a sustainable system like %Renew. SI was calculated at 2.83, indicating a transitional system. CCP was estimated at 780,000, exceeding the estimated total population of 810,000 by 23,000.

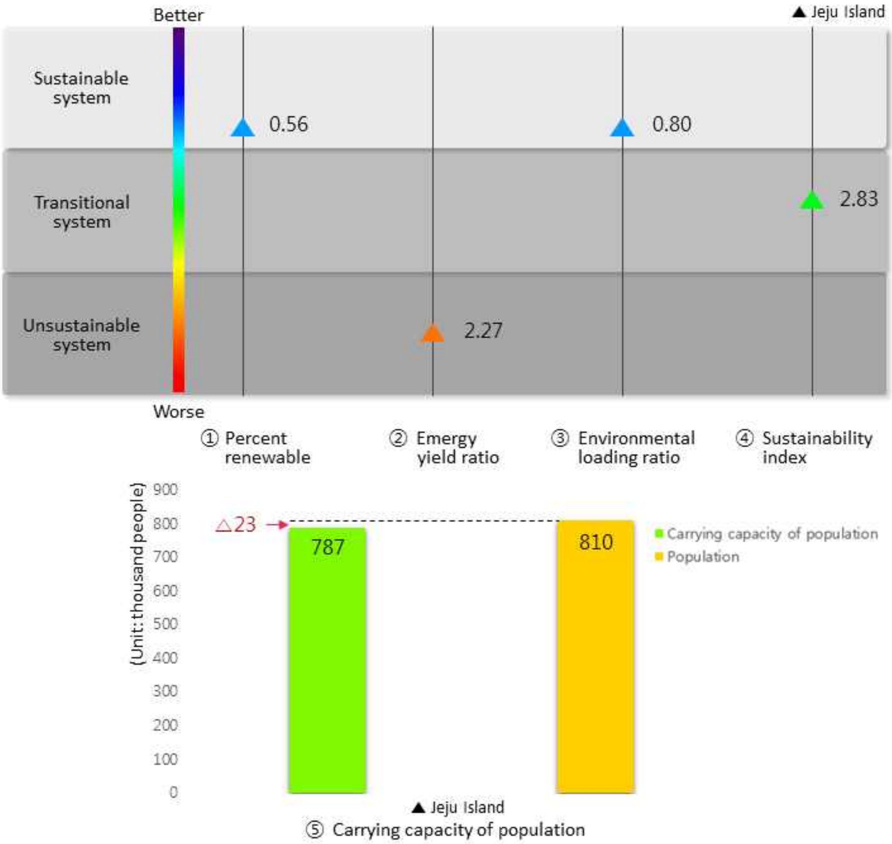


Figure 18 Five Emergy Indices Analysis considering System Stability in Jeju Island

2.2. Sustainability of Hainan

The variables needed to calculate the emergy index on Hainan were calculated as R for 1.63 × 10^{22} sej/year, N for 1.53 × 10^{20} sej/year, F for 5.45 × 10^{22} sej/year, and P2L for 3.29 × 10^{22} sej/year.

The results of Hainan's emergy indices for 2015 are shown in Figure 19. %Renew was calculated at 0.23, indicating a transitional system. EYR was estimated at 1.30, indicating an unsustainable system. ELR was 3.35, indicating a transitional system like %Renew. SI was calculated at 0.39, indicating an unsustainable system like EYR. CCP was estimated at 12,170,000, about 2,479,000 more than the total estimated population of 9,690,000. For Hainan, the %Renew, EYR, ELR, and SI results showed no index indicating a sustainable system, but the population was more acceptable.

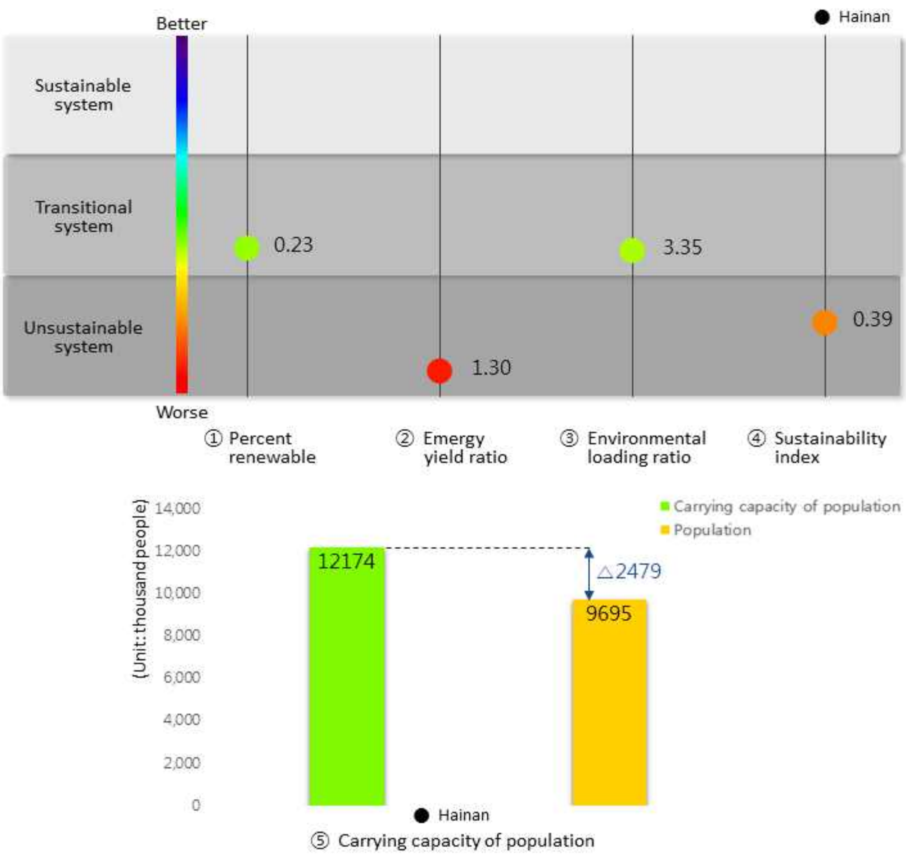


Figure 19 Five Emergy Indices Analysis considering System Stability in Hainan

2.3. Sustainability of Hawaii

The variables needed to calculate the emergy index for Hawaii were calculated as R for 1.08×10^{22} sej/year, N for 1.98×10^{20} sej/year, F for 3.71×10^{21} sej/year, and P2L for 5.94×10^{22} sej/year.

The results of Hawaii's emergy indices for 2015 are shown in Figure 20. %Renew was calculated at 0.73, indicating a sustainable system. EYR was estimated at 3.98, indicating a unsustainable system. ELR was 3.98, indicating a sustainable system like %Renew. SI was calculated at 11.02, indicating a sustainable system. CCP was estimated at 1,790,000, about 258,000 more than the total estimated population of 1,530,000.

For Hawaii, the %Renew, ELR, and SI results showed indices indicating a sustainable system, and the population was also more acceptable. Although EYR was analyzed as an unsustainable system, it seems that the degree of unsustainability is weak because the value of EYR is a transitional system starting from 4.

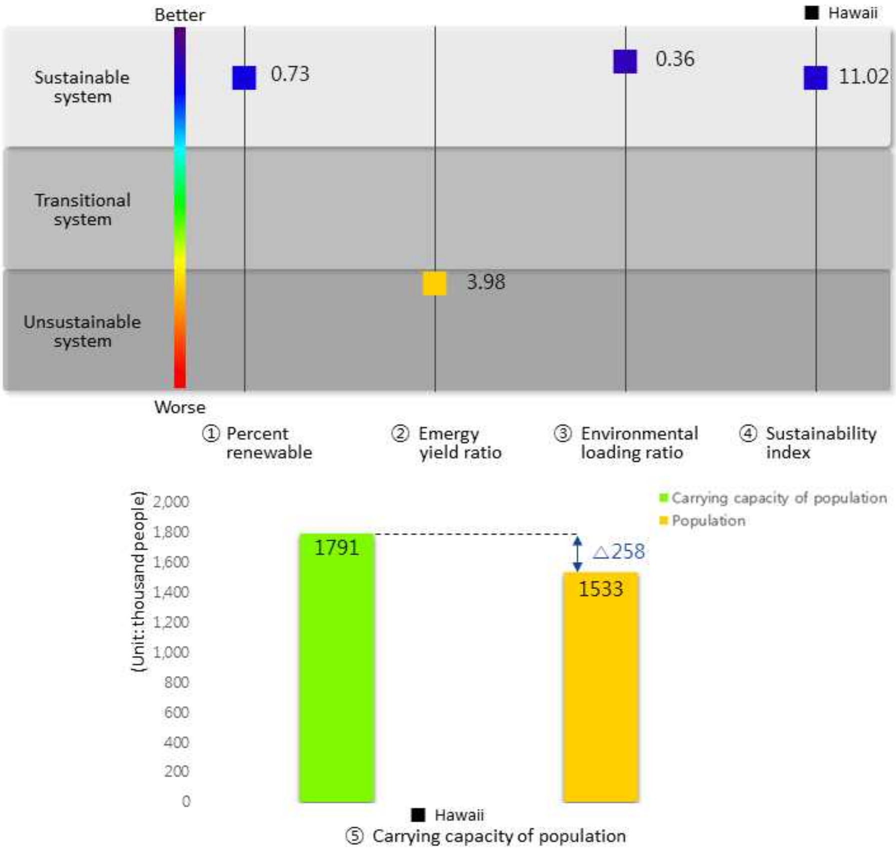


Figure 20 Five Emergy Indices Analysis considering System Stability in Hawaii

3. Comparative Analysis

3.1. Comparison of Emergy Evaluations

3.1.1. Total Emergy of Study Areas

The emergy of the representative resort islands in this study (Jeju Island, Hainan, and Hawaii) was estimated using emergy analysis and statistics in 2015. The results indicated that the total emergy of Hainan was highest at 1.68×10^{23} sej/year among the study areas, Hawaii at 1.03×10^{23} sej/year, Jeju Island at 2.12×10^{22} sej/year (see Figure 21). In particular, the total emergy of Hainan was 63% that of Hawaii's and

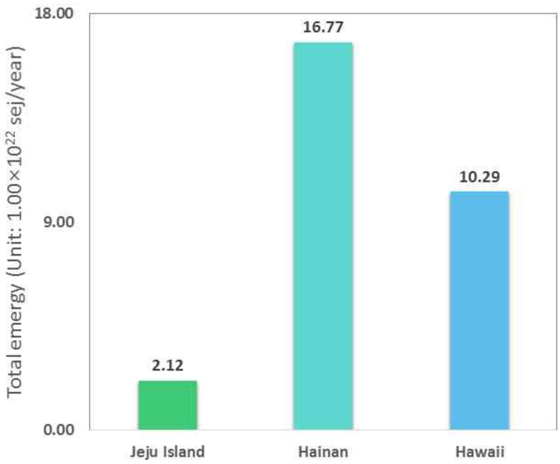


Figure 21 Total Emergy in Jeju Island, Hainan, and Hawaii

689% that of Jeju Island's, indicating that Hainan had social and economic activities than other regions.

Based on the emergy composition, the largest share of emergy of Jeju Island, Hainan, and Hawaii was IM emergy at 83%, 52% and 71%, respectively. RE emergy accounted for around 10% in all three regions, but Hainan ranked the highest in IR and EX emergy with 25% and 13%, respectively (see Figure 22).

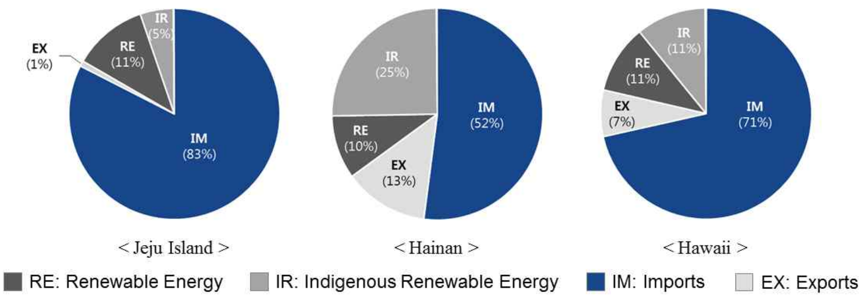


Figure 22 Emergy Composition in Jeju Island, Hainan, and Hawaii

3.1.2. Renewable Energy (RE) Category

The energy source with natural resources was calculated in the RE category. The emergy of sun item was calculated using the area and radiation, wind energy by wind speed and area, rain energy by precipitation and area, and wave energy by coastline length. These variables are difficult for humans to control, so it may not be meaningful to proceed with a comparison with the RE category. However, each region has its own characteristic of natural energy that could be used for sustainable development of the region.

In the RE category, the wave item had the largest amount of emergy on Jeju Island (2.43×10^{21} sej/year), Hainan (1.63×10^{22} sej/year), and Hawaii (1.08×10^{22} sej/year) (see Figure 23). Since these islands are surrounded by the sea, it was judged that the emergy in the wave item had more energy than other natural sources. Jeju Island had more emergy in the ranked order of the sun, wind, rain, and wave items, while Hainan had more emergy in the ranked order of the wind, rain, sun, and wave items. Hawaii had more emergy in the ranked order of the wind, sun, rain, and wave items. Hainan had the largest emergy in all RE category items compared to Jeju Island and Hawaii. It is believed that Hainan has the upper hand as Hainan has a larger area than Jeju Island and Hawaii, and the area is the variable that was used to calculate the emergy of the RE category.

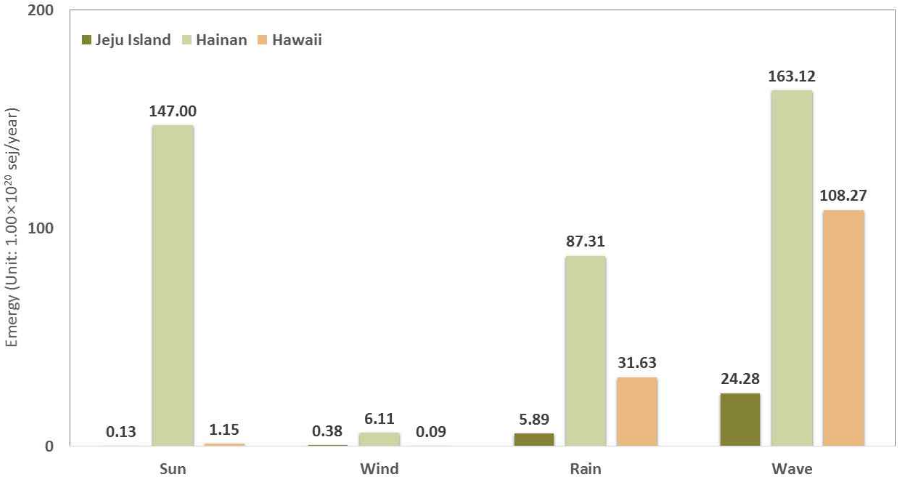


Figure 23 RE Category Emergy by Items in Jeju Island, Hainan, and Hawaii

3.1.3. Indigenous Renewable Energy (IR) Category

In the IR category, Hainan was calculated as 4.22×10^{22} sej/year, which was higher than Jeju Island and Hawaii. In particular, all of the IR category items (fisheries production, agricultural production, water extraction, electricity use, and forest extraction) of Hainan were determined to be higher than Jeju Island and Hawaii.

The results of the IR category per capita considering the total estimated population are shown in Figure 24 and Figure 25. Hawaii had the largest amount of emergy of electricity use and forest extraction when calculated per capita. For Jeju Island, the smallest amount of emergy was still recorded for the agricultural production, water extraction, and electricity use items. The amount of emergy in the IR category refers to the emergy that is produced and used in the region. These higher emergy levels indicate that more energy is available within the region for economic and social activities. Therefore, Hainan had the largest amount of emergy, which is attributed to the large estimated population residing in Hainan based on regional results. However, if the scope was narrowed to emergy per capita, the emergy of IR in Hawaii would be relatively better than Jeju Island and Hainan.

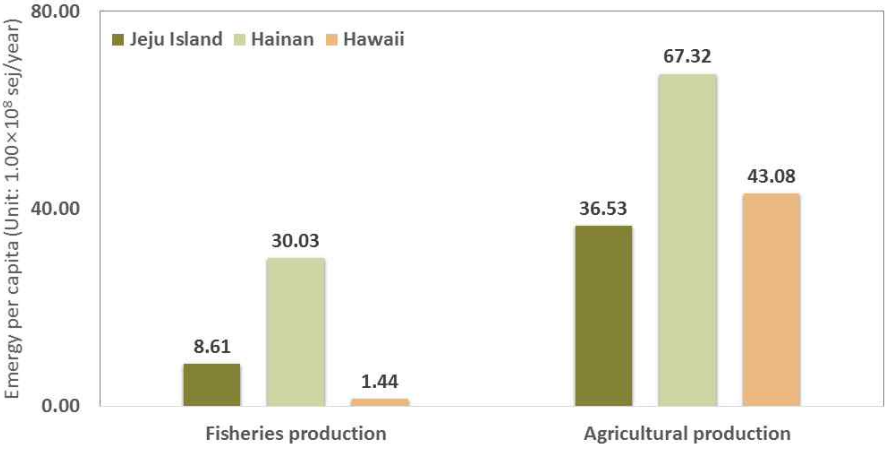


Figure 24 Emergy Per Capita of Fisheries Production and Agricultural Production in Jeju Island, Hainan, and Hawaii

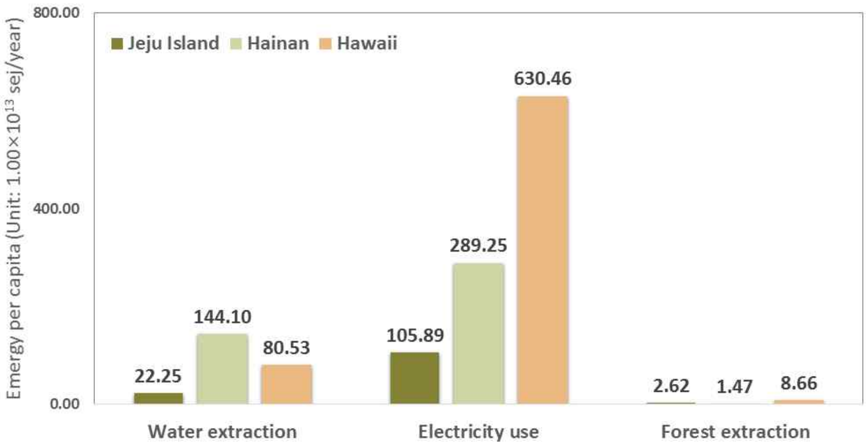


Figure 25 Emergy Per Capita of Water Extraction, Electricity Use, and Forest Extraction in Jeju Island, Hainan, and Hawaii

3.1.4. Nonrenewable Sources from Within System (NR) Category

Hawaii showed the largest amount of emergy (1.98×10^{20} sej/year) in the NR category (see Figure 26). In Hawaii, the distance from the mainland is relatively far compared to the distances for Jeju Island and Hainan, so it is more important to procure the necessary energy for economic and social activities within the region. Therefore, the soil becomes more common in production activities and is more eroded than other regions.

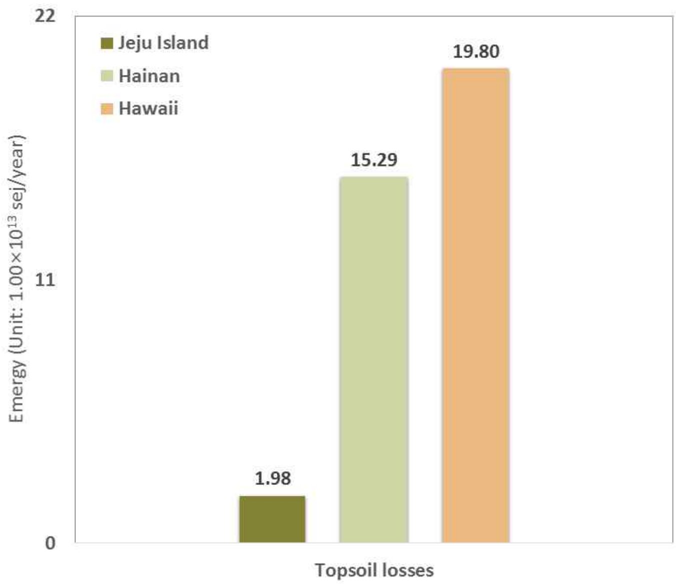


Figure 26 NR Category Emergy by Items in Jeju Island, Hainan, and Hawaii

3.1.5. Imports (IM) Category

Hainan showed the largest amount of emergy (8.74×10^{22} sej/year) in the IM category. The nonpermanent purchased emergy (the emergy of IM category except the tourism item) was also the highest estimated as 5.45×10^{22} sej/year.

Figure 27 shows the emergy results of IM category by items in Jeju Island, Hainan, and Hawaii. Hainan also had the highest value of 5.44 $\times 10^{22}$ sej/year for the fuels item. This is mainly due to satisfying the demand for fuel for economic and social activities of about the 9 million people living in Hainan and about 53 million people visiting Hainan, and fuel exports compared to Jeju Island and Hawaii. The emergy of the fuels item in Hawaii (4.29×10^{19} sej/year) was 32 times higher than that of Jeju Island (1.35×10^{18} sej/year). Jeju Island, unlike Hawaii, can import a portion of the electricity needed on land through HVDC. Thus, it is assumed that the amount of imported fuel is reduced by the amount of fuel required to produce the electricity.

Hawaii has the largest value of 1.16×10^{22} sej/year for the food and agricultural products item, and 2.10×10^{21} sej/year for the livestock, meat, fish item. These results relate to income levels. The average income of residents on Hawaii, Jeju Island, and Hainan is $54,270, $22,345, and $6,485 GDP per capita, respectively. Since GDP per capita and trade of food are highly correlated (Yang et al., 2007), Hawaii had the highest values for the food and agricultural products and livestock, meat, fish items, and Hainan had the lowest.

For the electricity item, Hainan and Hawaii did not have any emergy because they did not have a supply infrastructure such as the HVDC used by Jeju Island.

In IM category, Hainan had the highest value of emergy in the fuels item at 5.44 × 10^{22} sej/year, while Jeju Island and Hawaii had the highest value of emergy in the tourism item at 1.56 × 10^{22} sej/year and 5.94 × 10^{22} sej/year, respectively. The emergy of the tourism item in Hainan was 3.29 × 10^{22} sej/year, the second highest in the IM category. The energy flow of the tourism item was determined by the tourism revenue. Tourism energy flows on Jeju Island, Hainan, and Hawaii were \$4.10 × 10^{9}, \$8.65 × 10^{9}, and \$1.56 × 10^{10}, respectively.

If the energy flows are calculated as tourism revenue per capita, the

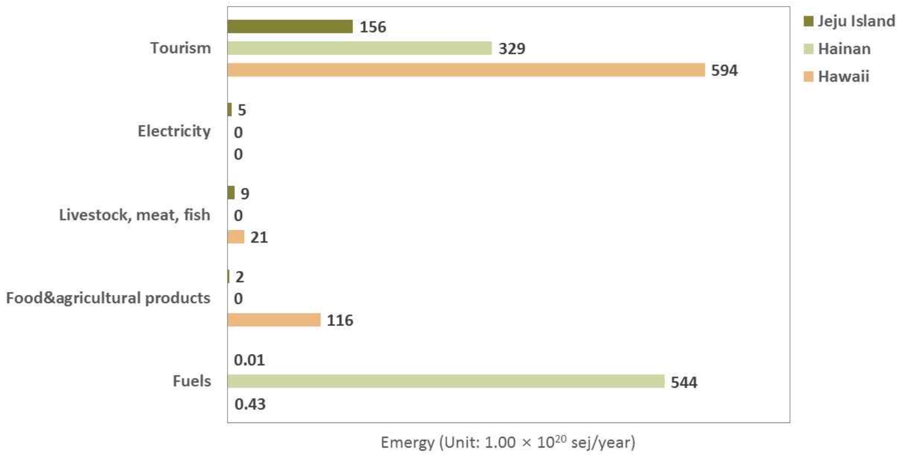


Figure 27 IM Category Emergy by Items in Jeju Island, Hainan, and Hawaii

flows on Jeju Island, Hainan, and Hawaii were $300, $162, and $1,828 (see Figure 28). Although Hawaii had the highest tourism revenue, Hainan had the highest number of tourists and Hawaii had the lowest number of tourists in 2015 (Hainan: 53,356,600 people; Jeju Island: 13,664,395 people; Hawaii: 8,533,978 people). Thus, it was analyzed that Hawaii had considerable tourism revenue from fewer tourists than Jeju Island and Hainan.

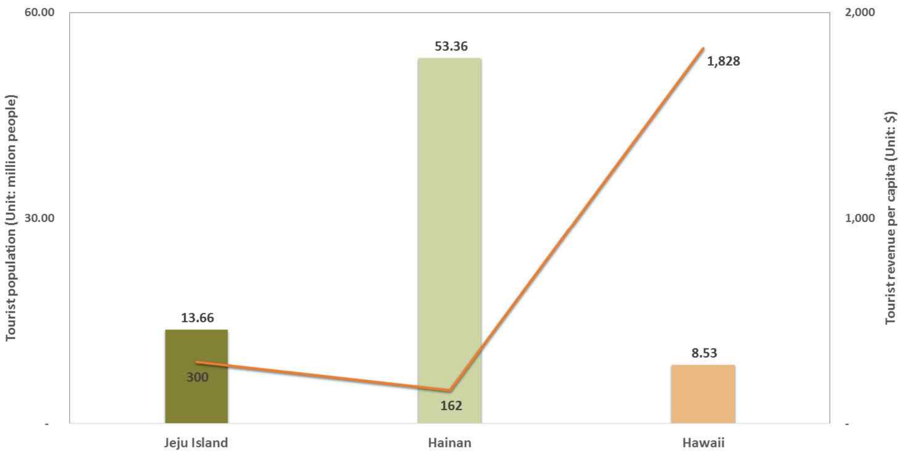


Figure 28 Tourist Population and Tourist Revenue in Jeju Island, Hainan, and Hawaii in 2015

3.1.6. Exports (EX) Category

Hainan showed the largest amount of emergy (2.17 × 10^{22} sej/year) in the EX category. Hainan had only three items in the EX category (fuels, food and agricultural products, chemicals), but it had the largest amount of emergy in the EX category (see Figure 29).

In addition, some emergy can be calculated only in certain regions in the EX category. The fuels item can only be calculated for Hainan, while the waste and scrap item can be calculated only for Hawaii.

The results indicated that Hawaii had the largest amount of emergy except the fuels and chemicals items. In addition, all items in the EX category of Jeju Island had lower levels of emergy than Hawaii.

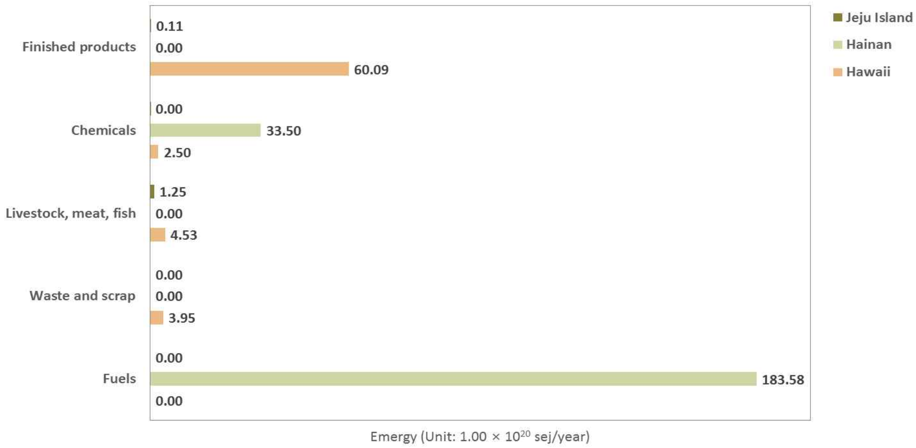


Figure 29 EX Category Emergy by Items in Jeju Island, Hainan, and Hawaii

3.2. Comparison of Sustainability Evaluations

3.2.1. Variables Results

The results of the variables, which include R (permanent emergy), N (nonpermanent emergy), F (purchased emergy), and P2L (goods and services emergy), in Jeju Island, Hainan, and Hawaii are shown in Figure 27. The variable R showed the highest value on Hainan at 1.63 $\times$ 10^{22} sej/year. Hainan has the longest coastline among the study areas because it is the largest resort island in the study. Thus, Hainan's wave emergy was the largest with the highest R value. The N variable in the study areas were judged to have little impact on the emergy index results as they were less valuable than the other variables.

The value of F, purchased emergy (i.e., the demand for purchasing emergy needed for economic and social activities), is the most remarkable variable in Figure 30. A high F value can be interpreted as a need for considerable emergy to satisfy the economic and social activities of many populations including tourists. The F value of Hainan was the highest (5.44 $\times$ 10^{22} sej/year), with 1370% in Hawaii (3.70 $\times$ 10^{21} sej/year) and 2731% in Jeju Island (1.92 $\times$ 10^{21} sej/year).

The P2L variable represents tourism emergy in this study, and since Hawaii had the highest tourism revenue, this variable was also the highest in Hawaii at 5.94 $\times$ 10^{22} sej/year. Hainan was calculated as 3.29 $\times$ 10^{22} sej/year and Jeju Island as 1.56 $\times$ 10^{22} sej/year. Combining

F and P2L, Hainan had a lower P2L value compared to a higher F (purchased emergy), while Hawaii had a higher P2L value compared to a lower F value. This represents the relationship between the tourist population and tourism revenue of Hawaii and Hainan.

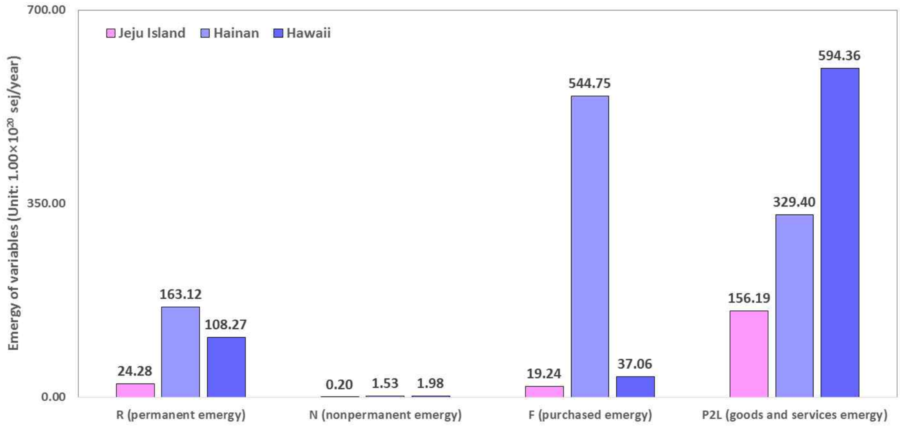


Figure 30 Variables Results for Evaluating Sustainability in Jeju Island, Hainan, and Hawaii

3.2.2. Results of Five Emergy Indices

The comparison of five emergy indices considering system stability in Jeju Island, Hainan, and Hawaii are shown in Figure 31. In %Renew, Jeju Island and Hawaii indicated a sustainable system, and only Hainan was a transitional system. The negative result of Hainan is believed to be because the F value (nonpermanent purchased emergy), which was needed to calculate the %Renew index, was 28 and 14 times higher than those of Jeju Island and Hawaii, respectively (see Figure 30). Hainan's high F value indicates the need to purchase the necessary emergy for economic and social activities of residents and tourists in the Hainan region. Since the estimated total population was the highest among the study areas, and fuels exports, which accounted for 99% of Hainan's F value, increased the amount. Hainan's R value was six times higher than that of Jeju Island and twice that of Hawaii, but the F value contributed more to the %Renew index. Thus, the result of Hainan's %Renew index was the worst.

EYR appears to be an unsustainable system on all three islands of Jeju Island, Hainan, and Hawaii. However, Hawaii had 3.98, which was close to the transitional system's standard value of 4, while Jeju Island and Hainan had lower levels. This result is also considered the best since Hawaii had relatively low F values. The F value on Jeju Island was smaller than Hawaii, but since the R and N values of Jeju Island were 22% and 10%, respectively, in Hawaii, the overall EYR value was lower than Hawaii.

ELR, like %Renew, indicated a sustainable system in Jeju Island and Hawaii, while Hainan indicated a transitional system. Hainan had the most negative ELR results because of its highest F value among the study areas. In Hawaii, the R value was four times higher than in Jeju Island, so the ELR was judged to have the best results.

For the SI index, Hawaii was analyzed as a sustainable system, Jeju Island as a transitional system, and Hainan as an unsustainable system. When calculating the SI index, EYR and ELR indices were used. The higher the EYR value, the better the result. Conversely, a smaller value of ELR means a better result. As a result, the EYR and ELR of Hawaii were the best in the study areas. In contrast, Hainan had the worst SI index.

Jeju Island showed population capacity saturation in the CCP index, but Hainan and Hawaii showed population capacity margins. Looking at the ratio of R to U required to calculate CCP, Jeju Island was calculated at 0.12, Hainan at 0.16, and Hawaii at 0.15. Multiplying the results by eight to represent the level of economic development in developed countries, Jeju Island was 0.96, Hainan was 1.28, and Hawaii was 1.2. Only the Jeju Island result was calculated below 1. These results indicate that only Jeju Island has a smaller population capacity than the current estimated population.

R, the CCP calculation variable, is an amount of emergy that can be obtained under a given condition, not by artificially adjustable variables such as solar radiation and wind speed. The results indicate that the

CCP of Jeju Island is saturated, with the largest number of tourists required for economic and social activities under natural conditions given to Jeju Island. Hainan can accommodate a population estimated at 1.28 times the total population because of its large area and abundant natural energy. These results indicate that Hainan has the largest population capacity margin among the study areas.

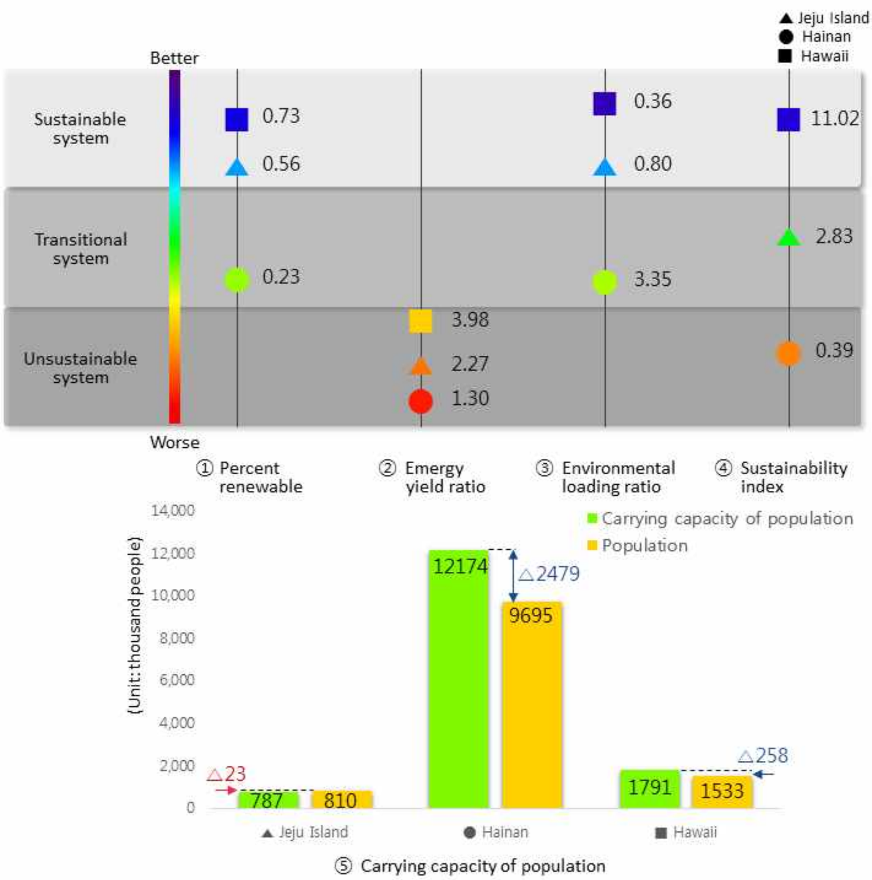


Figure 31 Comparison of Five Emergy Indices considering System Stability in Jeju Island, Hainan, and Hawaii

4. Sustainable Development Strategies of Resort Islands

4.1. Premium Tourism

There are several sustainable development strategies we can suggest based on the environmental carrying capacity results of the study areas. The first strategy is premium tourism. Premium tourism in this study is defined as a type of tourism that utilizes products and services with higher levels of quality to earn high tourism revenue with fewer tourist population.

Figure 32 shows the relationship between tourist population, tourism revenue, and the system stability of Jeju Island, Hainan, and Hawaii. Hawaii has the highest tourism revenue with the smallest tourist population among the study areas, and Hawaii belongs to a sustainable system. Conversely, Hainan has the least of tourism revenue despite having the largest tourist population, and Hainan belongs to an unsustainable system. Based on the results of this study, imports (IM) category emergy has a great influence on the environmental carrying capacity of the region, and tourism revenue is the most emergy in Jeju Island and Hawaii, and the second most in Hainan.

The transition to premium tourism can reduce the tourism population and decrease the F value which is the purchased emergy. These changes will help improving the environmental carrying capacity of resort islands that have a high relative tourist population.

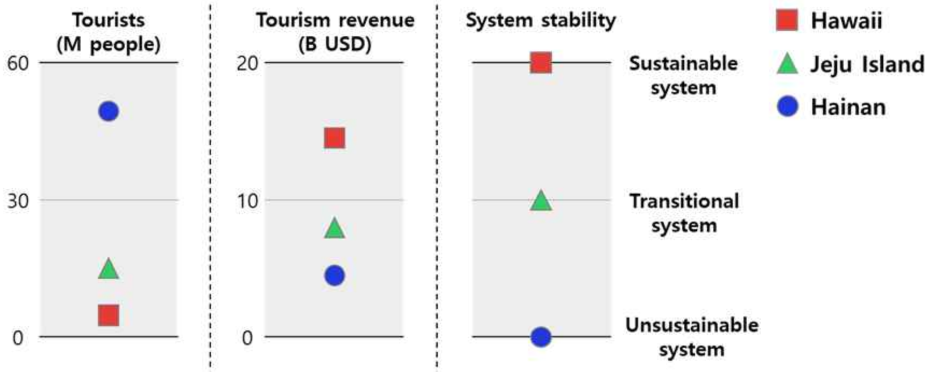


Figure 32 Relationship between Tourist Population, Tourism Revenue, and System Stability of Jeju Island, Hainan, and Hawaii

4.2. Renewable Energy

The second strategy is renewable energy. Increasing the use of renewable energy can reduce reliance on energy imports and production. In this study, Hainan had the largest amount of fuels import emergy among the study areas. Thus, the F value of Hainan was higher than other regions, which adversely affected the environmental carrying capacity and sustainability results. Jeju Island had the largest amount of electricity import emergy, which accounted for only 3% of Jeju island’s IM emergy. However, a renewable energy policy can help reducing the imported fuel used to produce electricity. In 2015, Jeju Island and Hainan’s renewable energy penetration rates are 9.3% (Jeju Special Self-Governing Province, 2016b) and 9.8% (ESCN, 2016), respectively (see Figure 33). On the other hand, the renewable energy penetration rate in Hawaii is 23.2% in 2015 (Hawaii Electric Light, 2016), and Hawaii is using less fuel to produce the needed power compared to Jeju Island and Hainan. If renewable energy is produced in a way that satisfies the power demand of the large tourist population, it can also reduce the F value and improve the environmental carrying capacity of the resort islands.

The renewable energy use policy is a necessary policy not only for tourism-centered islands but also for other regions. However, since island regions are not free from energy inputs and outputs, and are geographically isolated, island regions need to generate electricity based on their natural energy potential. In particular, this policy is deemed to be the most necessary for resort islands to take into account not only the resident population but also the tourist population.

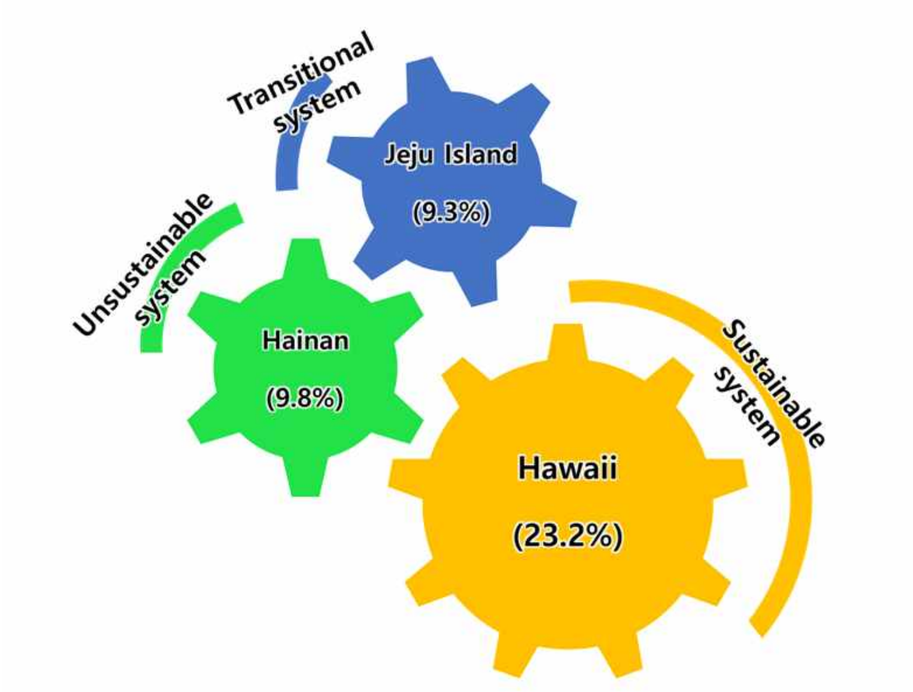


Figure 33 Relation between Renewable Energy Penetration Rate and System Stability

Chapter V. Conclusion

Islands typically have limited resources due to their isolated geographical characteristics, but in the case of a resort island, limited resources are used by both the resident population and tourist population. Resort islands have a larger share of tourists than other island regions because the tourism industry is a major industry that promotes the local economy. Therefore, it is necessary to evaluate the environmental carrying capacity that is acceptable to the ecosystem by considering the tourist population of these resort islands and to achieve sustainable development of resort islands through a sustainable development strategy.

This study evaluated the emergy of three popular resort islands (Jeju Island, Hainan, and Hawaii) in 2015 using an emergy analysis to determine the environmental carrying capacity of the region based on the results of the emergy index. In addition, this also study attempted to compare the environmental carrying capacity results across the three regions and present sustainable development strategies.

In 2015, the emergy by category on Jeju Island was calculated as RE 1.08×10^{21} sej/year, NR 1.98×10^{19} sej/year, IM 1.75×10^{22} sej/year, and EX 1.76×10^{20} sej/year. The emergy by category on Hainan was calculated as RE 1.63×10^{22} sej/year, IR 4.22×10^{22} sej/year, NR 1.53×10^{20} sej/year, IM 8.74×10^{22} sej/year, and EX

2.17×10^{22} sej/year. The emergy by category on Hawaii was calculated as RE 1.08×10^{22} sej/year, IR 1.10×10^{22} sej/year, NR 1.98×10^{20} sej/year, IM 5.99×10^{22} sej/year, and EX 7.33×10^{21} sej/year.

The regional emergy index was calculated based on the emergy evaluation by category as follows. Jeju Island was found to have a sustainable system in %Renew (0.56) and ELR (0.80), a transitional system in SI (2.83), and an unsustainable system in EYR (2.27). CCP was estimated to be about 780,000, so the total estimated population of Jeju Island exceeds the CCP by about 23,000. Hainan was found to have a transitional system in %Renew (0.23_) and EYR (1.30), and an unsustainable system in EYR (1.30) and SI (0.39). CCP was analyzed to have about 12,170,000 people. Hainan has a spare population capacity because it has more capacity than the total estimated population. Hawaii was found to have a sustainable system in %Renew (0.73), ELR (0.36), and SI (11.02), and an unsustainable system in EYR (3.98). CCP was analyzed to have about 1,530,000 people. Thus, Hawaii, like Hainan, has a spare population capacity. Therefore, the results of the emergy index showed that Hawaii had an environmental carrying capacity margin, and that this capacity decreased in order of Jeju Island and Hainan.

These results support a recommendation of sustainable development strategies such as premium tourism and renewable energy. Premium tourism can have the effect of reducing the tourist population, which can help decreasing the import emergy needed for their social and economic activities. Renewable energy policy can be developed by utilizing the infinite resources of the region, thereby reducing the emergy used for imported electricity and electric power production.

These strategies will help improve the environmental carrying capacity of the resort islands through the transition of premium tourism for less emergy demand and renewable energy polices for less overseas emergy dependence.

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Abstract in Korean

에머지 분석을 통한 휴양섬의 환경용량 평가와 지속가능한 발전 방안 연구

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환경용량은 수용력에서 발전한 개념으로 사람들의 특정한 활동을 수용할 수 있는 환경 능력을 의미 한다. 이러한 환경용량의 개념은 인류학, 지역개발, 도시 관리 등의 분야에서 의미를 다양하게 정의하고 있다. 특히, Catton은 환경용량을 생태학적 개념으로서 지속가능한 미래 환경을 파괴하지 않으면서 지속될 수 있는 이용의 규모로 해석하였다. 지역의 지속가능한 발전을 이루기 위해서는 미래의 지속성을 해치지 않는 범위 즉 환경용량 내에서 사람들의 경제 및 사회 활동을 위한 자원 소비가 이루어져야 한다. 이러한 환경과 지속성의 관계로 인해 환경용량은 지역의 지속가능한

발전을 평가하는 방법으로 사용되고 있다.

섬 지역은 지속가능한 발전을 분석하기 위한 좋은 연구 자료로 활용될 수 있는 것으로 알려져 있다. 섬은 사면이 바다로 둘러싸여있는 고립된 지역특성 상 제한된 자원을 통해 지속가능한 발전을 위한 투입물과 산출물의 측정이 가능하기 때문이다. 하지만 섬은 지리적으로 본토로부터 고립되어 있는 경향이 있기 때문에 섬의 생태계는 자연 재해 뿐만 아니라 국제 경제 성장이나 기후 변화와 같은 전지구적 영향에서 오는 변화에 민감하게 반응한다. 이러한 환경 취약성은 에너지 흐름을 포함한 섬의 자연 생태계에 위험을 줄 수 있다.

이러한 환경 취약성과 함께 휴양과 관광이 중심이 되는 휴양섬은 일반적인 섬과는 달리 거주인구뿐만 아니라 관광인구가 지역 환경에 미치는 영향이 반드시 고려되어야 한다. 제주도, 하와이, 하이난과 같은 휴양섬은 관광객들이 오락, 휴식 등의 목적으로 찾는 섬을 의미하며 이러한 섬들의 경우 관광인구의 비중이 상대적으로 매우 높게 나타난다. 2015년을 기준으로 거주인구 대비 관광인구 비중을 살펴 보면, 제주도는 2145%, 하와이는 598%, 하이난은 586%로 나타난다. 따라서 휴양섬의 지속가능한 발전 방안을 연구하기 위해서는 주어진 자원의 범위를 바탕으로 거주인구와 함께 관광인구를 고려하여 환경용량을 산정할 필요가 있다.

환경용량은 생태발자국, 오니시 모델, 시스템다이내믹스, 에머지 분석법 등과 같이 다양한 방법으로 산정이 가능하다. 생태발자국은 사람들의 경제활동을 유지하기 위해 필요한 수용력을 토지면적 단위로 환산하여 환경용량을 평가하는 방법이다. 생태발자국지수를 통한 환경용량평가는 경제 활동에 필요한 자원을 선정하고 해당 자원을 부문별로 나누어 자원생산에 소비되고 있는 1인당 토지면적을 산정한다. 산정된 지수를 바탕으로 해당 지역의 토지면적 사용량과 적정수준을 비교하여 환경용량을 평가할 수 있다.

오니시 모델은 환경적 제약범위 내에서 현재와 미래의 모든 사람들에게 일정 수준 생활의 질을 보장하는 것으로 목적으로 하는 환경용량 산정 방법이다. 사람들의 생활에 필요한 시설과 서비스의 수요 및 공급을 분석하고 수요와 공급의 불일치를 통해 해당 지역의 환경용량 초과 여부를 판단한다. 시스템다이내믹스는 복잡한 문제의 원인과 결과 분석을 통해 환경용량의 변화를 분석하는 방법론이다. 또한 정책 변화를 모델에 적용이 가능하기 때문에 환경용량 개선을 위한 정책 변화를 볼 수 있다는 장점이 있다. 에머지 분석법은 연구 대상지의 에너지 흐름을 분석하여 환경용량을 평가하는 방법이다. 또한 이는 지역 발전을 위해 투입된 에너지, 물질, 정보에 내재한 환경 부하 및 지속가능성을 평가하는 데 유효한 접근법으로 알려져 있다.

에너지 자원을 포함하여 자원의 수입과 수출을 바탕으로 환경용량을 산정하는 에머지 분석법은 휴양섬의 관광 산업 발전으로 인한 환경 부하와 지속가능한 발전을 신재생에너지 기술의 발달을 고려한 에너지 중심으로 평가가 가능한 장점이 있어 에머지 평가법을 선택하여 휴양섬의 환경용량을 평가하고자 하였다. 에머지 분석법을 이용하여 지역의 환경용량을 산정한 연구들은 다수 진행되어왔다. Chen et al.은 중국의 Yunnan Province를 대상으로 에머지 분석법을 통해 지역의 지속성을 평가하고, 이를 바탕으로 지속가능한 발전을 위한 정책을 제안하였다. 또한 Hossaini and Hewage는 캐나다의 에너지, 물질, 그리고 돈의 흐름을 분석하여 에머지를 평가하였다. 하지만 에머지 분석법을 활용한 대다수의 연구들은 고립된 섬 지역이 아닌 본토에 속해있는 지역을 대상으로 연구가 진행되었다. 또한 Zhang et al.과 Liu et al.의 경우 Zengcheng 지역의 관광수익을 변수로 포함하여 모든 경제적 요소를 고려한 지속가능성을 평가하여 제시하였지만, 휴양섬은 섬이 아닌 다른 지역에 비해 관광수익이 많을 것으로 기대되기 때문에 관

광객과 관광수익을 고려한 에머지 평가 결과가 다를 것으로 예상되었다.

따라서 본 연구에서는 대표적인 휴양섬인 제주도, 하이난, 하와이를 대상으로 에머지 평가법을 이용하여 환경용량을 평가하고 지역의 지속가능한 발전을 위한 정책을 제안하고자 하였다. 본 연구에서는 2장에서 환경용량, 에머지 분석법, 그리고 지속가능한 발전 전략과 관련된 연구들을 살펴보고, 3장에서 연구 대상지 및 에머지 분석법을 설명하였다. 그리고 4장에서 에머지 분석법을 이용하여 2015년 제주도, 하이난, 그리고 하와이 지역에서 에너지, 물질, 그리고 정보에 내재되어 있는 에머지를 평가하고, 평가된 에머지를 바탕으로 제주도, 하이난, 그리고 하와이의 에머지 재생가능도 (Percent renewable, %Renew), 에머지 생산비 (Emergy yield ratio, EYR), 환경부하율 (Environmental loading ratio, ELR), 지속성 지수 (Sustainability index, SI), 그리고 인구 수용력 (Carrying capacity of population, CCP)을 포함한 에머지 지수들을 산정하여 지역의 지속성을 분석하였다. 또한 제주도, 하이난, 그리고 하와이의 에머지 평가와 지속성 결과를 바탕으로 휴양섬의 지속가능한 발전을 위한 정책을 제안하였다. 5장에서 전체 내용을 종합하여 결론을 제시하고 있다.

본 연구에서 제주도, 하이난, 하와이를 대상으로 환경용량 산정에 사용한 에머지 평가법은 특정한 재화와 용역의 생산에 직접 및 간접적으로 투입한 모든 요소 (에너지, 물질, 정보 등)를 기준이 되는 에너지로 환산하여 이용가능 에너지의 합계로 정의할 수 있다. 또한 에너지를 생산하는 과정부터 사용되어지는 분야의 종류, 성격, 그리고 규모가 다르기 때문에 에머지 분석법에서는 이러한 에너지를 비교하기 위해 기준을 만들고 이를 바탕으로 각각의 에너지의 상대적인 능력을 비교한다. 에너지 능력의 차이를 환산시켜 주는 인자를 Unit Emergy Value (UEV)라고 한다. 현재 에머지 평가법에서 기준이 되는 에너지로 태양에너지를 사용하며, 이 경우 에머지를 태

양에머지 (Solar emergy)라고 부르고 UEV로 태양에머지 변환도를 사용한다.

에머지는 재생가능에너지 (Renewable energy, RE), 재생불가능에너지 (Nonrenewable source use from within system, NR), 비영속성에너지 (Indigenous renewable energy, IR), 수입에너지 (Imports, IM), 그리고 수출에너지 (Exports, EX)로 구성되어있다. 또한 각 카테고리에 해당하는 세부 항목들을 선정하고, 세부 항목들의 에너지 흐름과 태양에머지 변환도를 곱하여 해당 카테고리의 에머지를 산정한다.

각 카테고리별로 산정된 에머지량을 바탕으로 지역별 에너지 흐름의 시스템을 평가하고 환경용량의 지속성을 파악하기 위해 에머지 지수를 산정한다. 에머지 지수로는 에머지 재생가능도 (Percent renewable, %Renew), 에머지 생산비 (Emergy yield ratio, EYR), 환경부하율 (Environmental loading ratio, ELR), 지속성 지수 (Sustainability index, SI), 그리고 인구수용력 (Carrying capacity of population, CCP)이 있다. 이를 위해 산정된 에머지량을 영속성 에너지원 (R), 비영속성 보유 에너지원 (N), 비영속성 구입 에너지원 (F), 그리고 사용한 재화와 용역의 에머지 (P2L)로 구분하여 에머지 지수 산정식에 대입한다. 산정된 에머지 지수들을 바탕으로 세 종류의 시스템으로 그룹화하여 안정 시스템 (Sustainable system), 교란 시스템 (Transitional system), 그리고 불안정 시스템 (Unsustainable system)으로 구분하여 연구 대상지들의 환경용량과 지속가능성을 평가하였으며, 그 결과는 다음과 같다.

2015년 제주도의 카테고리별 에머지량은 RE가 2.43×10^{21} sej/year, IR이 1.08×10^{21} sej/year, NR이 1.98×10^{19} sej/year, IM이 1.75×10^{22} sej/year, 그리고 EX가 1.76×10^{20} sej/year을 기록하였다. 2015년 하이난의 카테고리별 에머지량은 RE가 1.63×10^{22} sej/year, IR이 4.22×10^{22}

sej/year, NR이 1.53 × 10^{20} sej/year, IM이 8.74 × 10^{22} sej/year, 그리고 EX가 2.17 × 10^{22} sej/year을 기록하였다. 2015년 하와이의 카테고리별 에머지량은 RE가 1.08 × 10^{22} sej/year, IR이 1.10 × 10^{22} sej/year, NR이 1.98 × 10^{20} sej/year, IM이 5.99 × 10^{22} sej/year, 그리고 EX가 7.33 × 10^{21} sej/year을 기록하였다.

산정된 카테고리별 에머지량을 바탕으로 지역별 에머지 지수를 산정한 결과는 다음과 같다. 제주도는 %Renew (0.56)와 ELR (0.80)에서 안정 시스템, SI (2.83)에서 교란 시스템, EYR (2.27)에서 불안정 시스템에 속해있는 것으로 나타났다. 그리고 CCP는 약 780,000 명으로 총 추정인구보다 약 2만 3천 명 초과하는 것으로 분석되었다. 하이난은 %Renew (0.23), EYR (1.30)에서 교란 시스템, EYR (1.30)과 SI (0.39)에서 불안정 시스템에 속해있는 것으로 나타났다. 하지만 CCP는 약 12,170,000 명으로 총 추정인구보다 약 2,479,000 명의 여유를 보이는 것으로 분석되었다. 하와이는 %Renew (0.73), ELR (0.36), 그리고 SI (11.02)에서 안정 시스템, EYR (3.98)에서 불안정 시스템에 속해있는 것으로 나타났다. 그리고 CCP는 약 1,530,000 명으로 총 추정인구보다 약 258,000 명의 여유를 보이는 것으로 분석되었다.

산정된 에머지 지수들의 결과를 종합하면 하와이가 환경용량 여유를 보이고 제주도, 하이난 순서로 환경용량이 감소하는 것으로 나타났다. 이러한 결과가 도출된 이유는 에머지 지수 산정에 변수로 이용되는 비영속성 구입에너지원 F 값에서 하이난이 제주도와 하아와이에 비해 각각 28배, 14배 높기 때문인 것으로 판단되었다. F 값이 높다는 것은 지역 내에 거주하고 체류하고 있는 지역 인구와 관광 인구가 많고 그들의 경제 및 사회활동에 필요한 구입 에너지가 많다는 것을 의미한다. 연구 대상지 중 하이난의 관광 인구가 2015년 기준 53,356,600 명으로 가장 많다. 이들의 경제 및 사회

활동에 필요한 에너지 수요를 맞추어주기 위해서는 많은 양의 에너지 유입이 필요하다. 하지만 1인당 관광수익을 산정해보면 하이난은 1인당 약 $162로 연구 대상지 중 가장 낮다. 반면 하와이의 관광 인구는 2015년 기준 연구 대상지 중 가장 적은 8,533,978 명이고 1인당 관광수익은 약 $1830로 가장 높다. 따라서 하와이는 관광 인구가 필요로 하는 구입 에너지원이 다른 지역들에 비해 적고 이는 하와이의 환경용량이 여유를 보이고 지속가능한 발전의 여지가 있다는 결과를 가지고 온 것으로 분석되었다.

본 연구에서는 에머지 분석법을 이용하여 대표적인 휴양섬인 제주도, 하이난, 그리고 하와이를 대상으로 에머지를 평가하고 에머지 지수 결과를 통해 지역의 환경용량을 판단하고 결과를 바탕으로 지속가능한 발전 방안을 제시하고자 하였다. 첫 번째로, 휴양섬이 지속가능한 발전을 이루기 위해서는 프리미엄 관광을 도입하는 것이 바람직 할 것으로 생각된다. 프리미엄 관광은 고품질의 제품과 서비스를 합리적인 가격에 제공하여 적은 관광인구로 높은 관광 수익을 얻는 형태의 관광을 의미한다. 연구 대상지 중 하와이는 가장 적은 관광 인구로 가장 높은 관광 수익을 얻고 있다. 즉 하와이는 고품질의 제품과 서비스를 다른 지역에 비해 높은 가격에 제공하는 프리미엄 관광을 적용하였다. 프리미엄 관광을 적용하면 관광 인구가 줄어들고 이는 관광 인구의 경제 및 사회활동에 필요한 에머지량이 줄어든다. 그리고 이러한 변화는 결과적으로 에머지 분석법으로 평가한 지역의 환경용량 개선에 도움을 주는 것으로 사료된다. 두 번째로, 신재생에너지의 이용을 늘려 전력 생산에 소비되는 연료의 수입을 줄이면서 에너지 수입 의존도를 줄이는 정책이 필요하다. 하이난은 연료 수입 과정에서 발생하는 에머지량이 수입 카테고리 항목 중에서 가장 높다. 그리고 제주도는 연료 항목의 에머지량은 적지만 전력을 본토에서 직접 수입해서 사용하고 있다. 하이난과 제주도 모두 전력 생산과 공급에 필요한 에머지량을 지역 내에서

생산 가능한 신재생에너지로 대체한다면 하이난의 경우 연료 항목의 에머지량이 적어지고, 제주도의 경우 전력 항목의 에머지량이 적어지게 되어 두 지역의 F 값을 낮추어 환경용량을 개선할 수 있을 것으로 판단된다. 이와 같이 여러 휴양섬들의 경우 관광 인구의 전력 수요를 충족시키기 위해 신재생에너지를 생산하여 제공한다면 지역의 환경용량을 개선하고 지속가능한 발전을 위한 정책 수립에 활용 가능할 것으로 생각된다.

Keywords : 에머지, 휴양섬, 환경용량, 지속가능한 개발

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