E4-EMERGY EVALUATION OF SOUTH KOREA'S SUSTAINABILITY PROGRESSION SINCE SIGNING THE KYOTO PROTOCOL

by

Hun Park

A dissertation submitted to the Faculty of the University of Delaware in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Energy and Environmental Policy

Fall 2015

E4-EMERGY EVALUATION OF

SOUTH KOREA'S SUSTAINABILITY PROGRESSION

SINCE SIGNING THE KYOTO PROTOCOL

by

Hun Park

Approved: ____
John Byrne, Ph.D.
Director of the Center for Energy and Environmental Policy

Approved: ____
George H. Watson, Ph.D.
Dean of the College of Arts and Sciences

Approved: ____
Ann L. Ardis, Ph.D.
Interim Vice Provost for Graduate and Professional Education

I certify that I have read this dissertation and that in my opinion it meets the academic and professional standard required by the University as a dissertation for the degree of Doctor of Philosophy.

Signed: ______________________________

Young-Doo Wang, Ph.D.
Professor in charge of dissertation

I certify that I have read this dissertation and that in my opinion it meets the academic and professional standard required by the University as a dissertation for the degree of Doctor of Philosophy.

Signed: ______________________________

Lado Kurdgelashvili, Ph.D.
Member of dissertation committee

I certify that I have read this dissertation and that in my opinion it meets the academic and professional standard required by the University as a dissertation for the degree of Doctor of Philosophy.

Signed: ______________________________

Daniel E. Campbell, Ph.D.
Member of dissertation committee

I certify that I have read this dissertation and that in my opinion it meets the academic and professional standard required by the University as a dissertation for the degree of Doctor of Philosophy.

Signed: ______________________________

Jung-Min Yu, Ph.D.
Member of dissertation committee

ACKNOWLEDGMENTS

Above all, I want to thank Dr. Wang, my teacher and advisor. He has been supportive of me all through my years in the PhD program. Before I settled with the research questions that lead to this study, I had changed my topic a few times. But Dr. Wang always encouraged me to pursue my research interest.

I cannot express my gratitude to Dr. Campbell enough. Had it not been for his help, I would never have completed the emergy evaluation for the study. In addition, although he is one of the world's foremost experts in energy systems theory, Dr. Campbell had been attentive to my naïve questions and smallest misunderstandings.

Dr. Yu's comments have polished my dissertation a lot. Because he understands the status quo of South Korea's sustainability far better than I do, I could adjust my discussion of the results and policy implications to reflect the raw reality of my home country.

It was Dr. Kurdgelashvili who found many mistakes in the draft which even I felt uncomfortable with but couldn't correct properly. His suggestions from different perspectives have upgraded the dissertation to be more scientific.

I apologize to every one of my friends and colleagues who feels unduly ignored. But I'll personally thank you one by one, however long it takes.

Lastly, I am immensely indebted to my extended family members. I love you. I love you. I love you. I'll be all yours through the rest of my life.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS AND ABBREVIATIONS

BOE	Bureau of Energy, Ministry of Economic Affairs (MOEA)
CAGR	Compound Annual Growth Rate
CHP	Combined Heat and Power
CIA	Central Intelligence Agency
DEU	Domestic Extraction Used
DGBAS	Directorate-General of Budget, Accounting and Statistics
DMC	Domestic Material Consumption
DMI	Domestic Material Input
EC	European Commission
ECEC	Ecological Cumulative Exergy Consumption
ED	Empower Density
EDO	emergy/money ratio
EFR	Emergy Footprint Ratio
EIA	U.S. Energy Information Administration
EIR	Emergy Investment Ratio
EISD	Emergy-based Index of Sustainable Development
ELR	Environmental Loading Ratio
EMR	Emergy to Money Ratio
EmSI	Emergy Sustainability Index
EP	Emergy use per Person
EPA	United States Environmental Protection Agency
EROI	Energy Return On energy Invested
ESI	Emergy Sustainability Index
ESL	Energy Systems Language
ESR	Emergy Self-support/sufficiency Ratio
EU	European Union
EUEHI	Emergy-based Urban Ecosystem Health Index
EXP	Total Exported Emergy
EYR	Emergy Yield Ratio
FAO	Food and Agriculture Organization of the United Nations
FIT	Feed-In Tariff
FRED	Federal Reserve Economic Data
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GIR	Greenhouse Gas Inventory & Research Center of Korea
GNP	Gross National Product

GTAP	Global Trade Analysis Project
HDI	Human Development Index
HSK	Harmonized System of Korea
ICCA	Institute for Climate Change Action
ICE	Internal Combustion Engine
IEA	International Energy Agency
IMP	Total Imported Emergy
INDC	Intended Nationally Determined Contribution
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
KCG	Korea Coast Guard
KCS	Korea Customs Service
KEEI	Korea Energy Economics Institute
KEI	Korea Environment Institute
KEMCO	Korea Energy Management Corporation
KEPCO	Korea Electric Power Corporation
KESIS	Korea Energy Statistics Information System
KHNP	Korea Hydro & Nuclear Power
KHOA	Korea Hydrographic and Oceanographic Administration
KIEP	Korea Institute for International Economic Policy
KIGAM	Korea Institute of Geoscience and Mineral Resources
KIOST	Korea Institute of Ocean Science & Technology
KITA	Korea International Trade Association
KLEMS	capital (K), Labor, Energy, Materials, and purchased Services
KMA	Korea Meteorological Administration
KORDI	Korea Ocean Research & Development Institute
KPX	Korea Power Exchange
LEI	Local Effect of Investment
LULUCF	Land Use, Land-Use Change and Forestry
MIFAFF	Ministry of Food, Agriculture, Forestry, and Fisheries
MKE	Ministry of Knowledge Economy
MLTM	Ministry of Land, Transport and Maritime Affairs
MOE	Ministry of Environment
MOF	Ministry of Oceans and Fisheries
MOGAHA	Ministry of Government Administration and Home Affairs
MOLIT	Ministry of Land, Infrastructure and Transport
NEA	Nuclear Energy Agency

NEAD	National Environmental Accounting Database
NEI	National Effect of Investment
NGCC	Natural Gas, Combined Cycle
NGII	National Geographic Information Institute
NGO	Non-Governmental Organization
NIER	National Institute of Environmental Research
NSSD	National Strategy for Sustainable Development
OECD	Organisation for Economic Co-operation and Development
PCGG	Presidential Committee on Green Growth
PCSD	Presidential Commission on Sustainable Development
PECOS	Public Engagement Commission on Spent Nuclear Fuel Management
PHWR	Pressurized Heavy Water Reactors
PMO	Prime Minister's Office.
PPP	Purchasing Power Parity
PWR	Pressurized Water Reactors
REC	Renewable Energy Certificate
RECS	Residential Energy Consumption Surveys
REYR	Regional Emergy Yield Ratio
RME	Raw Material Equivalent
RPS	Renewable Portfolio Standard
sej	solar emjoule
SMG	Seoul Metropolitan Government
SNA	System of National Accounts
TFEC	Total Final Energy Consumption
TPES	Total Primary Energy Supply
U	Total Emergy Use
UEHI	Urban Ecosystem Health Index
UEV	Unit Emergy Value
UN	United Nations
UNCED	United Nations Conference on Environment & Development
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
UNSD	United Nations Statistics Division
USGS	United States Geological Survey
WCED	World Commission on Environment and Development
WEC	World Energy Council

WHO	World Health Organization
WMO	World Meteorological Organization
WSSD	World Summit on Sustainable Development

ABSTRACT

Since signing the Kyoto Protocol in 1998, the South Korean government has promoted a series of climate policy instruments by implementing five comprehensive measure plans. “Have these plans been making any meaningful changes in the sustainability of South Korea?” To assess the progression of sustainability since the country began to develop those policy measures, this study adopted a conceptual framework for determining sustainability, which is called the ‘E4’ (economy, energy, environment, & equity) approach. To test whether each of the four aspects of E4 sustainability has been improving or declining, a specific method named ‘E4-Emergy evaluation’ was devised. E4-Emergy evaluation is based on emergy (spelled with an “m”) an accounting system that is expected to better assess a country’s sustainability in terms of its economy, energy, environment, and equity than can be obtained from the conventional energy accounts. Results of the evaluation were classified into each of the four ‘E’ sustainability categories. The indices and indicators synthesized from the results are compared with key well-known sustainability indicators that are produced from conventional energy accounting methods. In addition, the results of the E4-Emergy evaluation of South Korea were compared with those of 9 countries that have comparable emergy studies. After the evaluation and comparison, a number of policy implications are identified.

Chapter 1

INTRODUCTION

1.1 Problem Statement

1.1.1 History of integration between climate policies and national sustainable development strategies since signing the Kyoto Protocol

South Korea's involvement with the United Nations Framework Convention on Climate Change (UNFCCC) initiated the country's national interests in sustainability. Especially since signing the Kyoto Protocol in 1998, South Korea was forced to develop measures to deal with increasing international pressure to address one of the biggest environmental threats on the planet. Over time, the Korean people and their government became aware that climate policies couldn't be separated from national sustainability policies. In this section, the history of integration between climate policies and national sustainable development strategies is explained. And the history explains why the integrated sustainability evaluation covers the specific period between 1998 and 2010 (Table 1-1).

In the first *Comprehensive Measures on Climate Change* (PMO, 1999), the Korean government simply projected future greenhouse gas emissions using a bottom-up simulation model (the Long range Energy Alternatives Planning System, "LEAP"). So their measures were devised to decrease greenhouse gas emissions from each sector of Korean economy. In terms of sustainability, the plan focused on "sustainable growth" and counted South Korea as one of the developing countries of the world. The first government plan sounded very passive. In 1999, South Korea was still suffering from an unprecedented financial crisis and didn't have many resources available to deal with additional international pressure other than the economic reform measures imposed by the International Monetary Fund. It is also true that there were not many climate experts who would speak out against the then-prevalent economic recovery rhetoric.

A notable event between the first and second plans for comprehensive measures to address climate change is the establishment of the Presidential Commission on Sustainable Development (PCSD) in 2000. The Presidential Decree (Number 16946) that created the PCSD indicated that developing national countermeasures to climate change was one of the commission's four core functions (Y.-K. Chung & Hwang, 2006).

However, in the Second Comprehensive Measures on Climate Change (PMO, 2001) the Korean government began to seriously discuss 'global warming.' Although they had mentioned greenhouse emissions mitigation technologies in the first plan, the second plan became more specific. The plan stressed that energy technology policies should be at the core of the comprehensive measures. Especially, the plan called for government-wide support for research and development of technologies for improving energy efficiency or energy savings, and for developing low emission alternative energy technologies. In addition, to reduce emission intensity of the electric power sector, the plan demanded more nuclear power plants. In terms of mentioning 'sustainability,' compared to the first plan, the second plan moved toward advocating 'sustainable development' as defined by WCED (1987) rather than 'sustainable growth,' to reduce the government's emphasis on economic growth.

The *Third Comprehensive Measures on Climate Change* (PMO, 2004) advanced further. In addition to the ongoing sectoral climate change 'mitigation' policies, the plan began to institutionalize measures for 'adaptation' to climate change. To measure adaptation, the government decided to monitor the effects of climate change on people, infrastructure, and ecosystems. In addition, the concept of 'sustainability' remained the same in the third plan as it was in the second.

In addition, between the third and fourth plans, the PCSD announced Korea's first "National Strategy for Sustainable Development" (NSSD). In the government plan, climate change is one of four major strategies. The NSSD also designated greenhouse gas emission indices as core indicators of Korea's sustainable development (PCSD, 2006).

The efforts of Korea's response to international climate change became more systematic in the *Fourth Comprehensive Measures on Climate Change* (PMO, 2007). For the first time, the government mentioned 'environment-friendly Green Growth' in the plan. This plan also planned to announce the official mid- and long-term projection of greenhouse gas emissions.

However, the fourth plan was made by the outgoing government in 2007 and it was barely put into effect when the new government's *Comprehensive Basic Plan for Climate Change* (PMO, 2008) was announced. The new plan advanced the 'green growth' model and promoted a new phrase, "Low Carbon, Green Growth." In addition to traditional climate change policies, the new plan introduced measures for 'Eco Efficiency,' i.e., the efficient use of ecological resources and pollution reduction. With the fourth plan, the countermeasures to climate change were integrated with sustainable development. The integration of climate policy and national sustainable development strategies were reinforced by the *Five-Year Plan for Low Carbon, Green Growth (2009-2013)* (PCGG, 2009) and the "Framework Act on Low Carbon, Green Growth" (Act, 2010).

It was not until 2000 that Korea had a government-wide institution to cope with national agendas for sustainable development and national strategies for sustainability were not developed until 2006. However, in 1998, South Korea came under international pressure to deal with an urgent global environmental issue known as 'climate change.' The government's initially passive response to this pressure has evolved to become more active with four national countermeasure plans and one comprehensive countermeasure plan. Following climate policy development, national strategies for sustainable development were formulated. Finally, between 2009-2010, Korea's national climate policies and sustainable development strategies were institutionally integrated. Therefore, an integrated evaluation of South Korea's sustainability should begin from the year 1998 and follow the progression of sustainability until the latest year when all the data are available. At the time of the data analysis, the latest year for which all the data sets required for this study are available without missing parts was 2010.

Table 1-1: Integration of climate policies and national sustainable development strategies in South Korea

Year	Climate Policy	National Sustainable Development Strategy
1998	Signing of the Kyoto Protocol	
1999	1st Comprehensive Measures on Climate Change	
2000		Presidential Commission on Sustainable Development
2001	2nd Comprehensive Measures on Climate Change	
2004	3rd Comprehensive Measures on Climate Change	
2006		National Strategy for Sustainable Development
2007	4th Comprehensive Measures on Climate Change	
2008	Comprehensive Basic Plan for Climate Change	
2009	Five-Year Plan for Low Carbon, Green Growth (2009-2013)	
2010	Framework Act on Low Carbon, Green Growth	

1.1.2 South Korea's growth-oriented economic policies

Thirty-five years of Japanese imperialist colonial rule on the Korean peninsula came to an end in 1945. But it was not until 1948 that the United States Military Government gave way to South Korea's first modern government since independence[1]. However, the government did not have time to lead the country into recovery from the devastating effects of World War II, because the Korean War, a

[1] The preamble of the current *Constitution of the Republic of Korea* recognizes the Provisional Republic of Korea Government that was established in Shanghai, China, in 1919 (Republic of Korea, 1987). However, the effects of the provisional government's economic, energy, or environmental policies in Korea's sustainability are beyond this study's scope.

civil war between South and North Korea, erupted in 1950 and lasted for three years. The war made the Korean peninsula a desolate land. After the war, there was no operational industrial infrastructure and almost no natural resources. South Korea has negligible fossil fuel resources (Table 1-2) and the Nuclear Energy Agency identified no reasonably assured or inferred uranium resources in South Korea (NEA, 2012).

Table 1-2: Proved recoverable reserves at end-2008

a) Coal

	million tonnes
South Korea	126
Japan	350
China	114,500
United States	237,295
Russia	157,010
Australia	76,400
India	60,600
World	860,938

b) Natural gas

	billion cubic feet
South Korea	110
Japan	1,808
China	109,123
United States	244,656
Russia	1,585,644
Iran	1,045,677
Qatar	888,949
World	6,549,159

c) Crude oil and natural gas liquids

	million barrels
South Korea	2
Japan	68
China	18,052
United States	28,396
Saudi Arabia	264,063
Iran	137,610
Iraq	115,000
World	1,238,834

Source: WEC (2010).

After a decade of political turmoil, South Korea began industrialization with an authoritative reform put in place by a military government called the Third Republic. Ever since the Third Republic's economic reform in 1963, South Korea has for the most part pursued rapid economic growth (Noland, 2012). Even after the 1997-1998 Asian Financial Crisis, South Korea has held to a growth-driven economic policy. From 1998 to 2010, its real GDP has grown 5.07% per year. Although the growth rate was only half of China's annual growth rate (10.06%), it has achieved significantly higher GDP growth rates than those of other developed countries. During the same period, the annual growth rates of Japan, the United States, and the European members of OECD were 0.79%, 2.03%, and 1.78%, respectively (Table 1-3).

Table 1-3: Gross domestic product (GDP)

a) Real GDP
(unit: billion constant 2005 U.S. dollars)

	1998	2000	2005	2010	CAGR ('98-'10)
China	1,229	1,434	2,284	3,880	10.06%
Japan	4,221	4,308	4,572	4,639	0.79%
OECD Europe	12,550	13,412	14,763	15,510	1.78%
South Korea	563	678	845	1,019	5.07%
United States	10,214	11,158	12,564	12,992	2.03%

b) Nominal GDP
(unit: billion current U.S. dollars)

	1998	2000	2005	2010	CAGR ('98-'10)
China	1,045	1,193	2,284	5,951	15.60%
Japan	3,915	4,731	4,572	5,488	2.86%
OECD Europe	9,772	9,095	14,763	17,679	5.06%
South Korea	358	533	845	1,015	9.08%
United States	8,741	9,899	12,564	14,419	4.26%

c) Purchasing Power Parity GDP (unit: billion constant 2005 international dollars)

	1998	2000	2005	2010	CAGR ('98-'10)
China	2,888	3,368	5,364	9,122	10.06%
Japan	3,591	3,665	3,890	3,947	0.79%
OECD Europe	11,949	12,761	14,128	14,940	1.88%
South Korea	741	880	1,097	1,323	4.95%
United States	10,214	11,158	12,564	13,017	2.04%

Note. CAGR = Compound Annual Growth Rate.
Source: a) and b) from UNSD (2012); c) from World Bank (2013).

This economic growth has been driven by importing commodities in order to manufacture industrial goods for export (Table 1-4). The growth rates of the total weight of South Korea's traded commodities manifest the material requirements for supporting a growth-driven economy. It is no coincidence that annual growth rates of imported commodities (5.17%) and exported commodities (5.96%) are on a parallel to the annual GDP growth rate (5.07%). However, this economic growth strategy has resulted in an unsustainable situation with regard to energy use and environmental pollution.

Table 1-4: Cargo trades by South Korea (1000 metric tons)

	1998	2000	2005	2010	**CAGR ('98-'10)**
Imports	305,043	380,583	446,764	558,350	**5.17%**
Exports	107,620	135,584	156,102	215,499	**5.96%**

Source: KCS (2012b).

1.1.3 South Korea's energy system heavily depends on imported non-renewable energy

As Table 1-5 shows, from 1998 to 2010, South Korea's primary energy consumption increased by 58%. During the same period, the share of fossil fuels in South Korea's total primary consumption did not decrease, but hovered around 84%. Per capita energy consumption did not decrease, either. Rather it rose steadily, even during the global economic crisis which began in early 2007 (Edmonds, Jarrett, & Woodhouse, 2010; Federal Reserve Bank of St. Louis, 2011).

To make matters worse, well over 95% of South Korea's primary energy consumption depends on foreign energy sources (Table 1-5). In addition, South Korea's domestic energy base is very weak and its fossil fuel reserves are negligible; therefore, the country has to depend almost solely on renewable energy for its domestic energy resources. According to the Korean government's statistics, only 2.3% of South Korea's Total Primary Energy Supply (TPES) came from new and renewable energy in 2010. However, according to the OECD standards, the share of renewable energy sources is barely 1.6% of TPES. This number falls far short of figures from other developed countries such as Japan (3.6%), the United States (5.9%), and the OECD Europe (11.4%) (Table 1-6).

Table 1-5: Primary energy indicators in South Korea

Year	Primary energy consumption (1000 toe)	Component of primary energy							Per capita energy (toe)	Overseas dependence
		Fossil fuels				Hydro	Nuclear	New & renewable energy		
		Coal	Oil	LNG	Sub-total					
1998	165,932	21.7%	54.6%	8.4%	84.7%	0.9%	13.5%	0.9%	3.58	97.1%
1999	181,363	21.0%	53.6%	9.3%	83.9%	0.9%	14.2%	1.0%	3.89	97.2%
2000	192,887	22.3%	52.0%	9.8%	84.1%	0.7%	14.1%	1.1%	4.10	97.2%
2001	198,409	23.0%	50.7%	10.5%	84.2%	0.5%	14.1%	1.2%	4.19	97.3%
2002	208,636	23.5%	49.1%	11.1%	83.7%	0.6%	14.3%	1.4%	4.38	97.1%
2003	215,067	23.8%	47.6%	11.2%	82.6%	0.8%	15.1%	1.5%	4.49	96.9%
2004	220,238	24.1%	45.7%	12.9%	82.7%	0.7%	14.8%	1.8%	4.58	96.7%
2005	228,622	24.0%	44.4%	13.3%	81.7%	0.6%	16.1%	1.7%	4.75	96.6%
2006	233,372	24.3%	43.6%	13.7%	81.6%	0.6%	15.9%	1.9%	4.83	96.5%
2007	236,454	25.2%	44.6%	14.7%	84.5%	0.5%	13.0%	2.0%	4.86	96.5%
2008	240,752	27.4%	41.6%	14.8%	83.8%	0.5%	13.5%	2.2%	4.95	96.4%
2009	243,311	28.2%	42.1%	13.9%	84.2%	0.5%	13.1%	2.2%	4.99	96.4%
2010	262,609	28.9%	39.7%	16.4%	85.0%	0.5%	12.2%	2.3%	5.37	96.5%

Note. New & renewable energy = new energy (hydrogen, fuel cell) + renewable energy (IEA-compatible: solar thermal/photovoltaic, wind, biofuels, hydro, ocean energy, geothermal, renewable waste; IEA-incompatible: non-renewable waste).
Source: KEEI (2011).

Table 1-6: Share of energy sources in Total Primary Energy Supply (TPES) in 2010

Unit: Million tonnes of oil equivalent

	Renewables [a]	Fossil fuels [b]	Nuclear	Electricity	Heat	Total
South Korea	**3.99**	**207.21**	**38.73**	**-**	**0.09**	**250.01**
	1.6%	82.9%	15.5%		0.0%	100%
Japan	**17.75**	**403.97**	**75.11**	**-**	**-**	**496.85**
	3.6%	81.3%	15.1%			100%
United States	**131.40**	**1,864.06**	**218.63**	**2.23**	**-**	**2,216.32**
	5.9%	84.1%	9.9%	0.1%		100%
OECD Europe	**207.21**	**1,368.12**	**238.86**	**1.26**	**0.53**	**1,815.98**
	11.4%	75.3%	13.2%	0.1%	0.0%	100%
China	**283.98**	**2,115.06**	**19.25**	**-1.16**	**-**	**2,417.13**
	11.7%	87.5%	0.8%	0.0%		100%

Note. [a] Renewables: hydro, ‘geothermal, solar, etc.’, and ‘biofuels & waste’
[b] Fossil fuels: ‘coal & peat’, crude oil, oil products, and natural gas.
Source: IEA (2012b, 2012c).

South Korea’s energy use has not been particularly efficient. To generate the same amount of gross domestic product, it consumed more energy than other developed countries. In 2010, for example, South Korea consumed 50% more energy than Japan per unit GDP, 11% more than the United States, and 55% more than OECD Europe members (Figure 1-1).

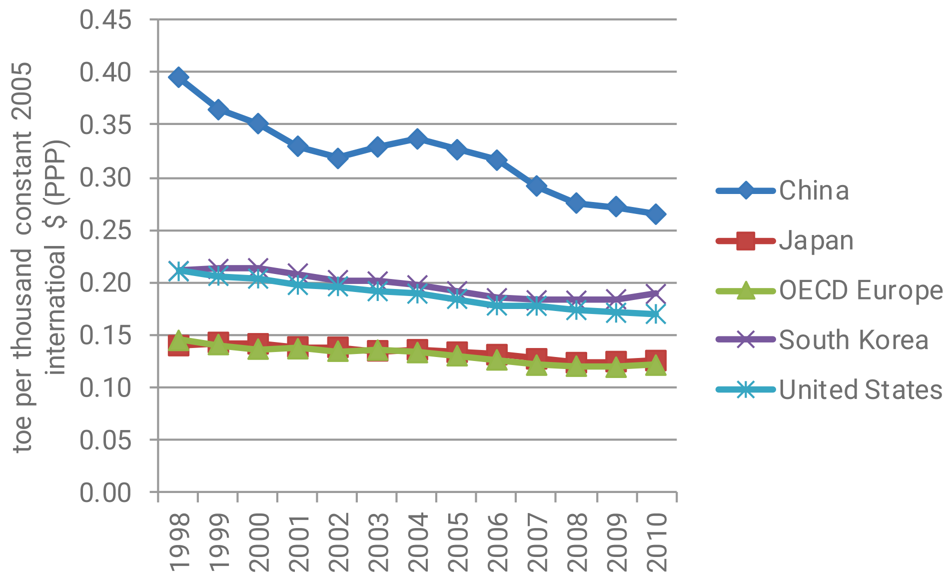


Figure 1-1: TPES per thousand 2005 international dollars of GDP at purchasing power parity (PPP).
Source: World Bank (2013); UNSD (2012).

1.1.4 South Korea's environmental performance

However, South Korea's five comprehensive measure plans on climate change (See Table 1-1) have not proved very effective. South Korea's annual greenhouse gas emissions have shown no decrease at all during the 1998-2010 period. In addition, greenhouse gas emissions from fossil fuel combustion have been increasing faster than other contributors to total emissions. Greenhouse gas emissions from fossil fuels increased at an annual growth rate of 4.05%, according to the South Korean government data (Table 1-7).

Table 1-7: Greenhouse gas emissions in South Korea

Unit: million tonnes of CO_2-equivalent

Year	Total GHG emissions	Land Use, Land-Use Change and Forestry (LULUCF)	Net GHG emissions	GHG emissions from fuel combustion
1998	437.4	-36.0	401.4	350.0
1999	478.9	-37.5	441.4	380.7
2000	512.1	-36.5	475.5	409.0
2001	530.4	-34.3	496.2	421.8
2002	548.4	-33.9	514.6	440.4
2003	559.5	-34.0	525.5	448.3
2004	566.9	-32.3	534.6	455.9
2005	568.8	-32.4	536.4	462.4
2006	575.4	-32.8	542.6	469.0
2007	590.3	-36.2	554.1	489.3
2008	604.1	-38.7	565.4	503.0
2009	609.1	-39.5	569.6	510.2
2010	668.8	-39.6	629.2	563.5
CAGR ('98-'10)	**3.60%**	**0.81%**	**3.82%**	**4.05%**

Source: Greenhouse Gas Inventory & Research Center of Korea (GIR) (2013).

This increase rate is remarkable especially when compared with those of other developed countries. Carbon dioxide emissions from fossil fuels increased at an annual growth rate of 4.02% from 1998 to 2010, according to the International Energy Agency. While South Korea's CO_2 emissions increased 60% over the same period, CO_2 emissions from Japan, the United States, and the OECD Europe have barely increased or even decreased during this time. This rapid increase in Korean greenhouse gas emissions is ominously closer to that of China, which showed 127% increase in CO_2 emissions from 1998-2010 (Table 1-8).

Table 1-8: Carbon dioxide emissions from fuel combustion

Unit: million tonnes of CO_2

Year	Korea	Japan	United States	OECD Europe	China
1998	351.0	1,129.3	5,479.4	3,959.8	3,197.3
1999	385.3	1,169.4	5,505.8	3,916.0	3,090.5
2000	437.7	1,184.0	5,698.1	3,954.6	3,077.2
2001	452.0	1,169.8	5,677.6	4,004.0	3,124.2
2002	446.1	1,205.5	5,605.2	3,986.6	3,347.8
2003	448.9	1,213.3	5,680.4	4,106.0	3,869.8
2004	469.8	1,212.5	5,763.5	4,132.3	4,592.8
2005	469.1	1,220.7	5,771.7	4,106.2	5,103.1
2006	476.6	1,205.0	5,684.9	4,141.8	5,644.7
2007	490.3	1,242.3	5,762.7	4,110.1	6,071.8
2008	501.7	1,154.3	5,586.8	4,037.6	6,549.0
2009	515.5	1,095.7	5,184.8	3,757.8	6,846.3
2010	563.1	1,143.1	5,368.6	3,859.8	7,258.5
2010/1998	**160%**	**101%**	**98%**	**97%**	**227%**
CAGR ('98-'10)	**4.02%**	**0.10%**	**-0.17%**	**-0.21%**	**7.07%**

Source: IEA (2012a).

1.1.5 South Korea's equity[2] impeded by unsustainable economic activities and energy consumption

As Figure 1-2 depicts, South Korea's income distribution shows a large difference between low income households and higher income households. The highest income decile has earned 9 to 11 times the income of the lowest income decile from 2003 to 2010. The income of the lowest income decile has been less than a quarter of the national average.

[2] The United Nations' efforts for sustainable development that began with the WCED's 1987 report "Our Common Future" and culminated with the UNCED's 1992 report "Agenda 21" have brought "social equity" into the global sustainability discourse (Theis & Tomkin, 2012). *Our Common Future* stated that a "world in which poverty and inequity are endemic will always be prone to ecological and other crises" (WCED, 1987) (Chapter 2, para. 4). *Agenda 21* asserted that the objective of "energy development, efficiency and consumption" should reflect "the need for equity" (UNCED, 1992) (para. 9.11). While the meaning of equity in the UN reports includes both inter-generational equity and intra-generational equity, the equity in this study will focus on the intragenerational social equity. This equity requires that all people have equitable access to resources and services that are provided by society and the environment (Dempsey, Bramley, Power, & Brown, 2011; Steffen & Stafford Smith, 2013).

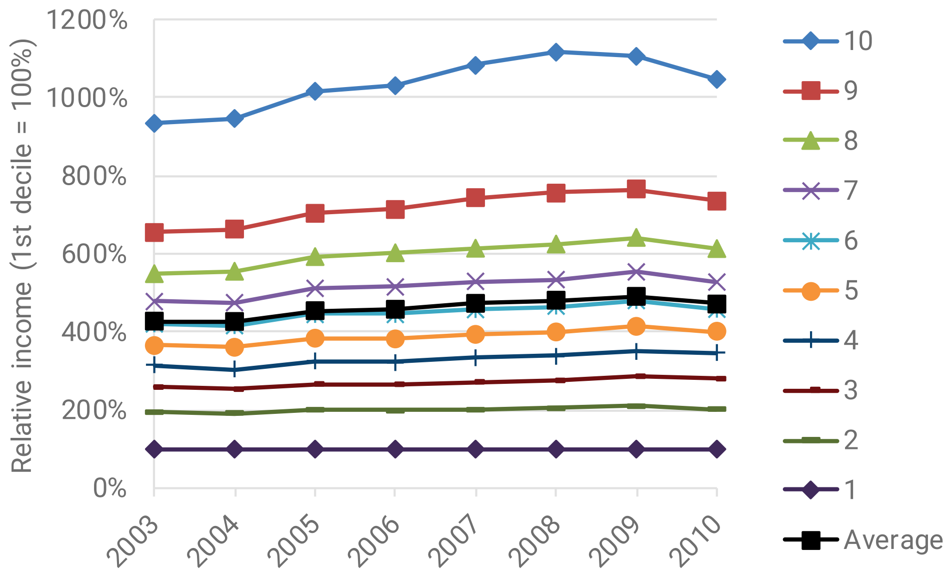


Figure 1-2: Household income distribution by monthly income decile.
Source: Statistics Korea (2012).

This unequal income distribution in South Korea is contrasted with energy consumption patterns by income groups. While income disparity has not been improving with the top 10%'s income being around 10 times that of the bottom 10% of households over the entire period of observation, fuel expenditure increased from 1998 to 2010 both in poor and wealthy households. Consequently, fuel expenditure's share in the poorest 10% of households' income has been increasing. In 2010, the bottom 10% of households spent 10.9% of their income on fuels, while the top 10% of households' fuel expenditure made up only 1.8% of their income (Figure 1-3).

a) b)

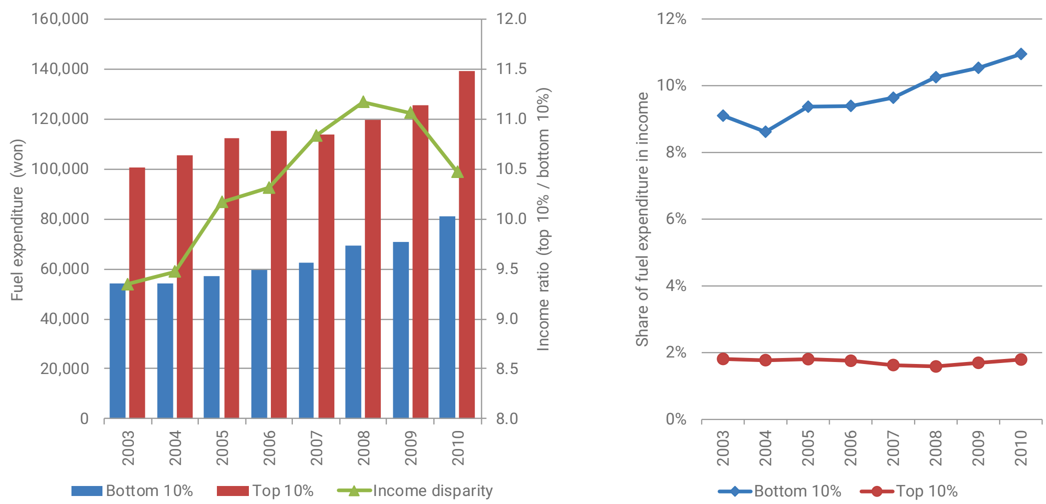


Figure 1-3: a) Fuel expenditure and household income and b) share of fuel expenditure in household income.
Source: Statistics Korea (2012).

1.1.6 Problems of the conventional energy accounting system in South Korea

The conventional energy accounting system itself is leading South Korea's policy makers astray by implying that it is acceptable to adopt and remain within an unsustainable national energy system.

First, South Korea's raw energy statistics offer little information about how energy use is related to societal patterns and environmental conditions in the country. The statistics report information about energy supply by fuel and technology and energy consumption by sector, but the statistics do not tell how the natural resources are affecting the energy supply chain or how the sectoral energy consumption is affecting the natural environment as a whole. Statistics on CO_2 emissions from fossil fuel combustion might be the only information about the energy sector's impact on the environment.

Above all, South Korea's energy statistics do not take the environmental impacts of different primary energy sources and energy end-uses into account. Although diverse energy sources emit different kinds and amounts of pollution, the external effects of energy conversion and delivery are not recorded in the energy statistics (Hall & Klitgaard, 2012). For example, the conventional energy statistics do not give any information about the environmental pollution that occurs during the mining, processing, and transporting stages of imported fossil fuels or uranium. Researchers are only able to calculate the amount of CO_2 emissions from domestic uses of those imported energy sources, and do not reckon with what has happened outside their own national borders.

Secondly, South Korea's energy statistics do not comply with thermodynamic principles. In the case of fossil fuels, the chemical energy embodied in fossil fuels is calculated and the energy losses during the conversion processes are tracked down in the statistics. However, in the case of non-fossil energy resources, the loss of primary energy during conversion is not properly accounted for (Giampietro & Sorman, 2012). For example, in South Korea's official energy statistics, the quantities of energy contained in the generated electricity were backward converted to be the quantities of primary energy in hydroelectric and nuclear energy (Table 1-9), using the predefined conversion factor of 1kWh of electricity being equal to 0.000215 toe (2,150 kcal) of fuels (KEEI, 2012b). The primary energy values in the table (1.391 million toe for hydro primary energy and 31.948 million toe for nuclear primary energy) were simply calculated by multiplying the quantities of electricity (6472 GWh from hydropower and 148596 GWh from nuclear power) (Table 1-10) by the conversion factor. There was no consideration of energy losses during the energy conversion. As a result, the official statistics didn't account for the amount of energy that was originally contained in these two non-fossil energy sources.

Table 1-9: South Korea's official energy flows in 2010 (1000 toe)

Energy source		Primary consumption	Transformation					Final consumption
			Total	Electric generation	District heating	Gas manufacturing	Own use & loss	
Coal	*Sub-Total*	77,092	-47,928	-47,928	-	-	-	29,164
	Anthracite	6,141	-390	-390	-	-	-	5,751
	Bituminous	70,951	-47,538	-47,538	-	-	-	23,413
Petroleum	*Sub-Total*	104,301	-3,920	-3,125	-317	-478	-	100,381
	Energy use	46,420	-3,418	-3,099	-317	-1	-	43,002
	LPG	10,924	-477	0	-	-476	-	10,448
	Non-energy use	46,956	-25	-25	-	0	-	46,931
LNG		43,008	-42,449	-18,548	-847	-22,778	-276	559
Town Gas		-	21,081	-922	-1,157	22,280	881	21,081
Hydro		**1,391**	**-1,391**	**-1,391**	**-**	**-**	**-**	**-**
Nuclear		**31,948**	**-31,948**	**-31,948**	**-**	**-**	**-**	**-**
Electricity		-	37,338	40,811	-	-	-3,474	37,338
Heat		-	1,718	1,073	713	-	-68	1,718
Renewable energy		6,064	-718	-718	-	-	-	5,346
Total		263,805	-68,218	-62,696	-1,609	-976	-2,937	195,587

Source: KEEI (2012b).

Table 1-10: Electricity generation by facility in 2010

	Total	Hydro	Nuclear	District energy	Alternative energy	Thermal power
Generation (GWh)	474,660	**6,472**	**148,596**	8,080	3,984	307,034
Share of total	100.0%	1.4%	31.3%	1.7%	0.8%	64.7%

Source: KEEI (2012b).

Just like other thermal power plants, hydropower and nuclear power plants have energy conversion losses. The energy efficiency for a modern large hydropower plant to convert water potential energy into electricity is 85-90% (Bostan et al., 2013; Kaunda, Kimambo, & Nielsen, 2012). The efficiency of small hydropower plants may be smaller, being about 60-70% (Choulot, Denis, & Punys, 2012). Meanwhile, the IEA assumes a thermal efficiency of 33% for nuclear power plants to convert the heat produced from the reactor to electricity in its energy statistics, even while the organization is not considering how much energy the nuclear fuels contained in the first place (IEA, 2005).

However, in the conventional energy accounting system, the primary energy supply (= consumption) numbers for hydro-power and nuclear energy are simply thermal equivalents of the actual electric power generated by each energy source. Therefore, in the official energy statistics, 1 toe of hydro energy cannot be the same as the same thermal equivalent quantity of coal or crude oil. In this regard, the sum of the primary energy supply, called total primary energy supply or TPES, is not the exact sum of the various kinds of energy supplied. To evaluate the true sustainability of a country's energy system, an accounting method that evaluates different energy sources in a scientifically proven common unit is mandated.

Third, the present energy accounting system makes it difficult to assess the performance of past energy and climate change policies with regard to equity. Generally, a household's energy consumption increases as their income rises, although the choice of energy sources differs depending on income levels (Jamasb & Meier, 2010; Meier, Jamasb, & Orea, 2013). However, South Korea's energy statistics do not distinguish between the quality of different energy sources. It is not easy to analyze exactly which primary energy sources were most often used by better-off people at the point of end-use and which primary sources were consumed by the poorest people in the country. Because there certainly is a difference between exploiting pollution-emitting fuels and utilizing clean renewable energy sources, information about which kinds of primary energy sources were used by which income groups in Korea should serve to set guidelines for energy and climate policy development. For example, a carbon tax would impose greater burdens on low-income families, who are probably living in less energy-efficient houses (Murphy, 2012).

1.2 Research Objectives and Research Questions

1.2.1 Research objectives

Based on the problems stated in the previous chapter, research objectives in this study are identified as follows.

- Finding a suitable energy-based accounting system (e.g., "emergy") to better assess South Korea's energy sustainability than is possible using the conventional means.

- Further developing the alternative energy accounting system in order to additionally account for the equity dimension and temporal changes in the energy system.
- Assessing South Korea's integrated sustainability in terms of the alternative energy accounting system, and laying out policy implications.

1.2.2 Research questions

Based on the research objectives, the following research questions were raised.

1.2.2.1 Finding a suitable energy-based accounting system (e.g., "emergy") to better assess South Korea's energy sustainability than is possible using the conventional means.

- **What is emergy?**: The theory and basic methodologies of the alternative energy accounting scheme will be presented from a literature review.
- **What is different about the alternative energy accounting method ("emergy") compared to the traditional methods?**: First, the advantages of the alternative energy accounting method compared to the conventional methods will be explained. Second, the weak points of the alternative energy accounting method for producing a sustainable energy system account will be explained.

1.2.2.2 Further developing the alternative energy accounting system in order to additionally account for the equity dimension and temporal changes in the energy system.

Because the alternative energy accounting system (i.e., “emergy”) must address some issues to comprehensively assess energy sustainability, some additional components should be integrated into it.

- **How can the lack of methods to address equity within the emergy methodology be rectified?**: To expand the applicability of the adopted energy accounting system, theories and methods to integrate additional data containing indicators for equity will be researched.
- **How can the E4-emergy data become a multi-year database?**: Because a single year’s data cannot provide sufficient information about the impacts of climate policy on a national energy system, a time series database on the new energy-equity accounting system will be developed.

1.2.2.3 Assessing South Korea’s integrated sustainability in terms of the alternative energy accounting system, and laying out policy implications.

- **What are useful indicators that the E4-emergy accounting system can generate in order to assess integrated sustainability of South Korea?**: Using the time series E4-emergy database, a number of sustainability indicators will be synthesized. Time series changes of those indicators will assess the progression of E4-sustainability from 1998-2010.
- **What are unique policy implications that only the E4-emergy accounting system can provide?**: Characteristics which are germane only to sustainability indicators that are synthesized from the E4-

emergy database will be explained and used to find policy options that will improve South Korea's integrated sustainability.

Chapter 2

LITERATURE REVIEW AND THEORETICAL FRAMEWORK

2.1 Energy Systems Theory and Emergy Accounting

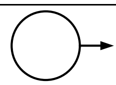
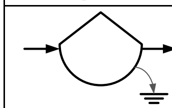
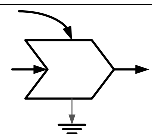
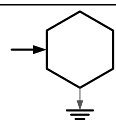
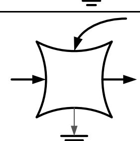
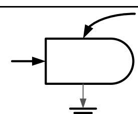
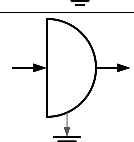
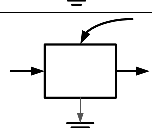
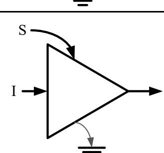
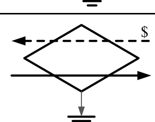
Howard T. Odum developed the field of scientific inquiry eventually called "Energy Systems Theory" concomitantly with the introduction of an "energy network language", the Energy Systems Language (ESL) (Odum, 1967), which was originally called the "energy circuit language" (Odum, 1971, 1983, 1994). This tool for systems analysis utilizes mathematically-defined symbols to construct network diagrams of all kinds of systems. Because even materials, information, and money have a certain amount of energy, all these pathways have energy flows. So ESL diagrams can represent all kinds of "energy systems" (Odum, 1983, 1994, 1996). The ESL gradually evolved into an Energy Systems Theory encompassing systems ecology and thermodynamics (Odum & Odum, 2000).

Therefore, Odum needed a universal measure of energy that could fit into his Energy Systems Theory (Odum, 1996). To facilitate a systems analysis, he and his colleagues had to convert all units of energy, resources, and services into one kind. Although they first used a term "embodied energy" for the universal measure of energy (Odum, 1983), they found that the term was causing confusion with another 'embodied energy' used in other fields for calculating the amount of non-renewable energy stored in a resource (Brown & Herendeen, 1996; Ulgiati, 2000). In 1987, David M. Scienceman proposed a new term "emergy" (from 'energy memory') as a substitute for 'embodied energy' and the emergy scientists officially adopted it (Odum, 2007, p. 100; Scienceman, 1997). Later, emergy was formally defined as "the available energy of one kind previously used up directly and indirectly in transformations to make a product or service" (Odum, 1994, p. 251). The unit of emergy is the emjoule, which denotes the past use of available energy, i.e., the joules of many kinds expressed in terms of a single kind, e.g., solar energy. In most emergy analysis including this study, "solar emergy" is used to express all of the energy material and information flows evaluated.

2.1.1 Emergy Systems Language symbols and diagrams

Odum and later his students and his colleagues recognized how effective symbols and diagrams can be for understanding the structure and processes in complex systems (Brown, 2004). Symbols are diagrammed for the flows, storages, intersections, and feedbacks of energy, materials, information, money, etc. Symbols must retain energy constraints and precise mathematical definitions to represent relationships between units (symbols) in systems. These symbols are summarized in the following table.

Table 2-1: Symbols of the Emergy Systems Language

Symbol	Name	Explanation
	Energy circuit	A pathway whose flow is proportional to the quantity in the storage or source upstream.
	Source	Outside source of energy delivering forces according to a program controlled from outside; a forcing function.
	Tank	A compartment of energy storage within the system storing a quantity as the balance of inflows and outflows; a state variable.
	Heat sink	Dispersion of potential energy into heat that accompanies all real transformation processes and storages; loss of potential energy from further use by the system.
	Interaction	Interactive intersection of two pathways coupled to produce an outflow in proportion to a function of both; control action of one flow on another; limiting factor action; work gate.
	Consumer	Unit that transforms energy quality, stores it, and feeds it back auto-catalytically to improve inflow.
	Switching action	A symbol that indicates one or more switching actions.
	Producer	Unit that collects and transforms low-quality energy under control interactions of high-quality flows.
	Self-limiting energy receiver	A unit that has a self-limiting output when input drives are high because there is a limiting constant quality of material reacting on a circular pathway within.
	Box	Miscellaneous symbol to use for whatever unit or function is labeled.
	Constant-gain amplifier	A unit that delivers an output in proportion to the input ***I*** but is changed by a constant factor as long as the energy source ***S*** is sufficient.
	Transaction	A unit that indicates a sale of goods or services (solid line) in exchange for payment of money (dashed line).

Source: Odum (1996, p. 5)

2.1.2 Empower and total global emergy inflow

To conduct an emergy analysis on a system, for example, to analyze a country, the emergy flows involved in a unit time should be calculated. The flow of emergy per unit time is called “empower,” just as the meaning of power is the flow of energy per unit time. Empower is for the most part computed over a year-long period of time for country-scale systems.

To ascertain the total global emergy inflow (empower) is very important in emergy accounting, because the total global empower becomes the ultimate baseline of the total empower in the studied system and all UEVs.

According to the Energy Systems Theory, all major energy flows on Earth ultimately derive from one of three sources: solar insolation, deep Earth heat, and tidal energy absorbed (Most by the oceans). The total solar insolation is 3.93×10^{24} joule per year, the total energy from deep Earth heat is 4.07×10^{24} joule per year, and the total tidal energy absorbed by the oceans is 1.26×10^{24} joule per year. The transformity of solar energy is 1.0 solar emjoules per joule (sej/J) by definition.

Therefore, the total emergy inflow (global empower) into the global geobiosphere is approximately 9.26×10^{24} sej per year (Table 2-2). This total global empower is also called the “emergy baseline” (Odum, 1996, p. 39).

Table 2-2: Annual emergy inputs to the global geobiosphere

Source	Energy flux (J/yr)	Solar transformity (sej/J)	Empower (sej/yr)
Solar insolation	3.93E+24	1	3.93E+24
Deep earth heat	6.72E+20	6,055	4.07E+24
Tidal energy	8.515E+19	14,797	1.26E+24
Total global empower			9.26E+24

Source: D. E. Campbell (2000); Odum (1996).

Because emergy takes into account any energy coming from all three sources, it is one of very few sustainability indicators that cover all kinds of renewable resources (Loiseau, Junqua, Roux, & Bellon-Maurel, 2012).

2.1.3 Unit Emergy Values

The unit conversion factors used to transform various forms of energy into emergy are called "unit emergy values" (UEVs) (Brown, Raugei, & Ulgiati, 2012). The UEV is basically the emergy per unit energy or unit mass.

2.1.3.1 Transformity

When the UEV is the emergy per unit energy, it is specifically called "transformity." The most widely used transformity is solar transformity. Solar transformity is the solar emergy required to make one joule of a service or product. The unit of solar transformity is a solar emjoule per joule (sej/J). By definition, the solar transformity of sunlight is 1 sej/J.

For example, transformities for fossil fuels are as follows. Natural gas has a larger transformity value than coal does, because it requires more work from nature to produce the same amount of energy.

Table 2-3: Transformities for fossil fuels

Fossil fuel	Transformity (sej/J)
Coal	39,200
Crude oil	54,200
Natural gas	43,500

Note. Planetary emergy baseline = 9.26E+24 sej/yr
Source: Bastianoni, Campbell, Susani, and Tiezzi (2005).

2.1.3.2 Specific emergy

If the UEV is the emergy per unit mass, it is also called "specific emergy." Its unit is solar emjoule per gram (sej/g) (Odum, 1996; Ulgiati, Agostinho, et al., 2011).

For example, some specific emergy values of minerals and products are listed below. Here, the higher value of steel's specific emergy (1.47×10^{10} sej/g) over that of iron ore (7.09×10^{9} sej/g) means that more energy and materials have been used to forge steel than simply to mine iron ore. In the same sense, more energy and materials are needed to convert lime (1.61×10^{9} sej/g) to cement (2.68×10^{9} sej/g) than simply to mine the limestone.

Table 2-4: Specific emergies of some minerals and products

Unit: sej/g

Item	Specific emergy
Aluminum (content)	3.16E+09
Cement	2.68E+09
Copper	5.73E+10
Gold	2.92E+11
Iron Ore	7.02E+09
Lead	2.81E+11
Lime	1.61E+09
Nitrogen (content)	6.84E+09

Item	Specific emergy
Phosphate (rock)	1.75E+10
Potash (K_2O)	1.71E+09
Salt	9.81E+08
Silver	2.63E+11
Steel	1.47E+10
Sulfur	8.89E+10
Tin	9.94E+11
Zinc	4.11E+10

Note. Numbers are expressed relative to the 9.26E+24 sej/yr planetary baseline.
Source: Campbell and Lu (2009).

2.1.4 An illustrated explanation of key terms in emergy accounting

In order to understand the core concepts related to emergy, the second law of thermodynamics must be explained: "In any transfer or conversion of energy within a closed system, the entropy of the system increases." (Dincer & Rosen, 2007, p. 8) That is, the quality of energy degrades at each transfer or conversion.

Let us think of a biofuel that contains 1 joule of energy. In this case, the amount of energy (1 J) is called "available energy" or "exergy" in thermodynamics. In comparison, the emergy of the biofuel is not equal to the available energy. Emergy is a sum of the exergy (or available energy) after converting the inputs to energy of one kind that has been used up (degraded directly and indirectly during transformations) to make the biofuel (Odum, 1996).

To illustrate the concepts more easily, a simplified energy flow according to the emergy theory can be drawn using the symbols introduced above. While one million joules of sunlight is transformed into 1 J of biofuel, if no human intervention is considered, the emergy contained in each resource remains constant at 10^6 sej. This means that whether 1 J of fuel, 10^2 J of feedstock, or 10^4 J of biomass are involved, they all need the same 10^6 J of sunlight for their production.

Only the conversion factors between the exergy and emergy of each resource are different. The conversion factors are their unique "transformities" and are shown in the figure below. In other words, 1 J of biofuel has used up 10^6 J of sunlight in the making, whereas 1 J of fuel feedstock requires 10^4 J of sunlight and 1 J of biomass requires only 10^2 J of sunlight. In this sense, transformity (and all UEVs) is "a kind of efficiency measure" (Brown & Ulgiati, 2004, p. 330).

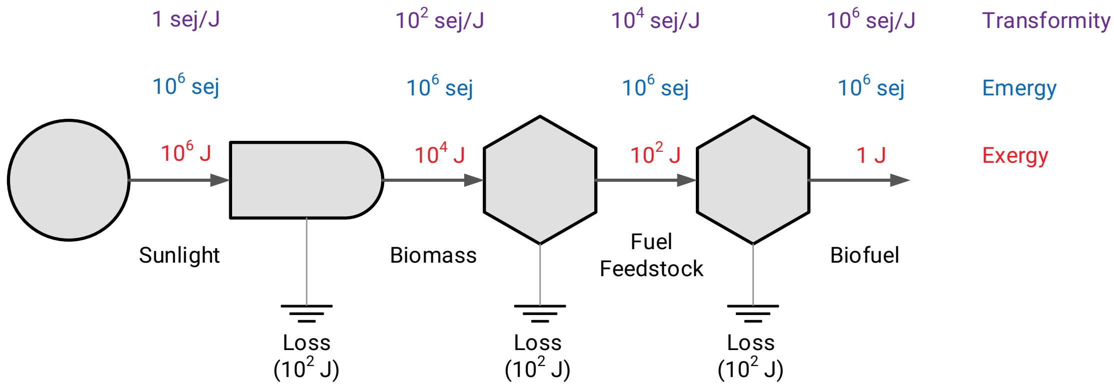


Figure 2-1: Exergy flow and transformation in biofuel production.
Source: Bakshi, Baral, and Hau (2011).

2.1.5 Emergy accounting procedure

After preparing raw data, the actual emergy accounting begins. Emergy accounting consists of three steps: (1) drawing a systems diagram of all inflows and outflows, (2) constructing tables of the actual flows of materials, labor (human resources), and energy, and (3) emergy evaluation sometimes called "emergy synthesis" or "emergy analysis" that interprets the quantitative results and ends with calculating several emergy indices (Brown & Ulgiati, 2004; Siche, Agostinho, Ortega, & Romeiro, 2008). In the following paragraphs, the procedure will be explained in detail.

First, a system diagram of all inflows and outflows is drawn. This study will follow Ulgiati and Brown (1998) and Morandi, Campbell, and Bastianoni (2014) to define renewable, nonrenewable, and feedback flows. That is, the renewable flows (R) are (i) flow limited (the rate they flow through the system cannot be increased), (ii) free (they are available at no cost), and (iii) locally available. The nonrenewable flows from within (N) are (i) stock limited (the rate of withdrawal or exploitation can be increased, but the total available amount is finite in the time scale of the system) (ii) not always free (sometimes a cost is paid for their exploitation), and (iii) locally available. The feedback flows (F) are (i) stock limited, (ii) never free, and (iii) never locally available, always imported. The following figure is an example of how basic emergy flows are interacting in a simple system.

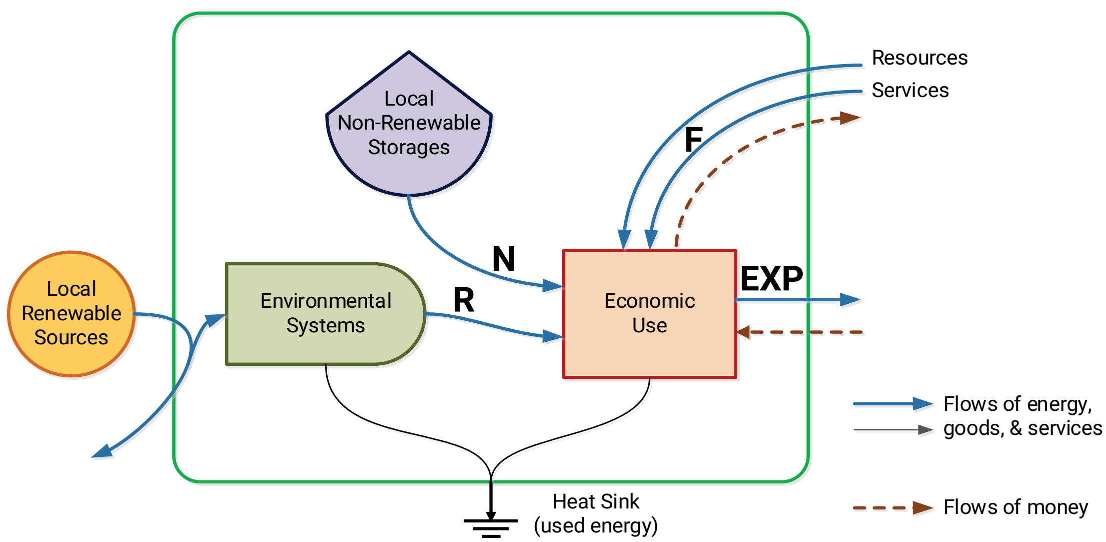


Figure 2-2: Basic emergy flows in a simple system.
Source: Based on Brown and Ulgiati (2004).

Second, tables of the actual flows of materials, labor (human resources), and energy are constructed. Using all the material and energy flows within the system, emergy flows are calculated by multiplying the raw data by their unique unit emergy values. In the following table, a summary of annual flows of resources for South Korea is presented. Respective transformities for each resource are also added in the table with their reference sources. The entire analysis is conducted over the period of 1998-2010.

Table 2-5: Annual inflow, production, and use of resources for South Korea in 2010

No	Sym-bol	Item		Raw value	Unit	Solar transfomity (sej/unit)	Solar emergy (sej/yr)	Transformity source
	Renewable Sources							
1	R	Sun		5.83E+20	J/yr	1	5.83E+20	By definition
2		Wind, kinetic energy		5.49E+17	J/yr	1.47E+03	8.06E+20	(Odum, 1996)
3		Rain, chemical (land)		7.04E+17	J/yr	1.81E+04	1.27E+22	(D. E. Campbell & Ohrt, 2009)
4		Rain, chemical (shelf)		2.04E+17	J/yr	1.81E+04	3.69E+21	(D. E. Campbell & Ohrt, 2009)
5		Rain runoff, chemical		4.08E+17	J/yr	1.81E+04	7.39E+21	(D. E. Campbell & Ohrt, 2009)
6		Rain runoff, geopotential		2.23E+17	J/yr	2.72E+04	6.07E+21	(Odum, 1996)
7		Waves		3.15E+17	J/yr	3.00E+04	9.44E+21	(Odum, 1996)
8		Earth cycle		1.89E+17	J/yr	3.37E+04	6.38E+21	(Odum, 1996)
9		Tide		1.26E+18	J/yr	2.43E+04	3.07E+22	(D. E. Campbell, 2000)
	Nonrenewable Sources from within System							
10	N	Net forest loss			J/yr			
11		Net fisheries loss			J/yr			
12		Topsoil loss		9.05E+16	J/yr	7.26E+04	6.57E+21	(Odum, 1996)
13		Coal production		3.97E+16	J/yr	3.92E+04	1.55E+21	(Odum, 1996)
14		Natural gas production		2.26E+16	J/yr	4.35E+04	9.83E+20	(Bastianoni et al., 2005)
15		Metallic minerals		6.49E+11	g/yr	1.55E+10	1.01E+22	(D. E. Campbell, Lu, & Lin, 2014)
16		Nonmetallic minerals		9.29E+13	g/yr	4.25E+09	3.95E+23	(D. E. Campbell, Lu, & Lin, 2014)
	Imported Sources							
17	F	Fuels	Sub-total				6.24E+23	
17-a			Anthracite	1.91E+17	J/yr	3.92E+04	7.50E+21	(Odum, 1996)
17-b			Bituminous for iron & steel	6.85E+17	J/yr	3.92E+04	2.68E+22	(Odum, 1996)
17-c			Bituminous for steam	2.22E+18	J/yr	3.92E+04	8.69E+22	(Odum, 1996)
17-d			Crude oil	5.08E+18	J/yr	5.42E+04	2.75E+23	(Bastianoni et al., 2005)
17-e			Petroleum products	1.13E+18	J/yr	6.47E+04	7.33E+22	(D. E. Campbell & Ohrt, 2009)
17-f			Natural gas (LNG)	1.77E+18	J/yr	4.35E+04	7.72E+22	(Bastianoni et al., 2005)
17-g			Uranium	1.59E+18	J/yr	4.81E+04	7.65E+22	(D. E. Campbell & Ohrt, 2009)
18		Metallic minerals		6.10E+13	g/yr	1.08E+10	6.57E+23	(D. E. Campbell, Lu, & Lin, 2014)
19		Nonmetallic minerals		5.31E+12	g/yr	1.07E+10	5.71E+22	(D. E. Campbell, Lu, & Lin, 2014)
20		Metal products		4.10E+13	g/yr	7.76E+09	3.18E+23	(D. E. Campbell & Ohrt, 2009)
21		Cements		8.39E+11	g/yr	2.03E+09	1.70E+21	(Brown & Buranakarn, 2003)
22		Food and agricultural products		3.39E+17	J/yr	1.96E+05	6.66E+22	(Brown & McClanahan, 1996)
23		Livestock, meat, fish		9.09E+15	J/yr	1.96E+06	1.78E+22	(Brown & McClanahan, 1996)
24		Plastics and rubber		2.46E+12	g/yr	2.71E+09	6.66E+21	(D. E. Campbell & Ohrt, 2009)
25		Chemicals		1.58E+13	g/yr	2.75E+09	4.35E+22	(D. E. Campbell, Brandt-Williams, & Meisch, 2005)
26		Finished materials	Sub-total	2.05E+13	g/yr		1.30E+22	
26-a			Leather products	2.84E+11	g/yr	7.18E+06	2.04E+18	(D. E. Campbell & Ohrt, 2009)
26-b			Lumber & wood products	7.41E+12	g/yr	7.90E+04	5.85E+17	(D. E. Campbell & Garmestani, 2012)
26-c			Paper	5.03E+12	g/yr	2.22E+05	1.12E+17	(D. E. Campbell & Garmestani, 2012)
26-d			Textile	1.88E+12	g/yr	7.18E+06	1.35E+19	(D. E. Campbell & Ohrt, 2009)
26-e			Glass & ceramics	5.02E+12	g/yr	2.12E+09	1.06E+22	(Brown & Buranakarn, 2003)
26-f			Others	8.45E+11	g/yr	2.75E+09	2.32E+21	(D. E. Campbell, Brandt-Williams, & Meisch, 2005)
27		Machinery, transportation equipment		5.99E+12	g/yr	7.76E+09	4.65E+22	(D. E. Campbell & Garmestani, 2012)
28		Services in imports		4.25E+11	$/yr	1.20E+12	5.10E+23	(Global U)/GWP (This study)

	Exports							
29	EXP	Petroleum products		1.79E+18	J/yr	6.47E+04	1.16E+23	(D. E. Campbell & Ohrt, 2009)
30		Metallic minerals		2.86E+11	g/yr	1.05E+11	3.00E+22	(D. E. Campbell, Lu, & Lin, 2014)
31		Nonmetallic minerals		8.10E+11	g/yr	1.12E+10	9.07E+21	(D. E. Campbell, Lu, & Lin, 2014)
32		Metal products		2.87E+13	g/yr	7.76E+09	2.23E+23	(D. E. Campbell & Ohrt, 2009)
33		Cements		7.58E+12	g/yr	2.03E+09	1.54E+22	(Brown & Buranakarn, 2003)
34		Food and agricultural products		2.47E+16	J/yr	1.96E+05	4.84E+21	(Brown & McClanahan, 1996)
35		Livestock, meat, fish		3.22E+15	J/yr	1.96E+06	6.32E+21	(Brown & McClanahan, 1996)
36		Plastics and rubber		1.41E+13	g/yr	2.71E+09	3.82E+22	(D. E. Campbell & Ohrt, 2009)
37		Chemicals		2.17E+13	g/yr	2.75E+09	5.96E+22	(D. E. Campbell, Brandt-Williams, & Meisch, 2005)
38		Finished materials	Sub-total	7.54E+12	g/yr		3.29E+21	
38-a			Leather products	7.97E+10	g/yr	7.18E+06	5.72E+17	(D. E. Campbell & Ohrt, 2009)
38-b			Lumber & wood products	5.22E+10	g/yr	7.90E+04	4.12E+15	(D. E. Campbell & Garmestani, 2012)
38-c			Paper	3.41E+12	g/yr	2.22E+05	7.56E+16	(D. E. Campbell & Garmestani, 2012)
38-d			Textile	2.73E+12	g/yr	7.18E+06	1.96E+19	(D. E. Campbell & Ohrt, 2009)
38-e			Glass & ceramics	3.57E+11	g/yr	2.12E+09	7.56E+20	(Brown & Buranakarn, 2003)
38-f			Others	9.14E+11	g/yr	2.75E+09	2.51E+21	(D. E. Campbell, Brandt-Williams, & Meisch, 2005)
39		Machinery, transportation equipment		3.05E+13	g/yr	7.76E+09	2.37E+23	(D. E. Campbell & Garmestani, 2012)
40		Services in exports		4.66E+11	$/yr	2.80E+12	1.31E+24	(R+N+F)/GDP (This study)

Third, an emergy evaluation is carried out by interpreting the quantitative results and generating emergy indices. How the emergy flows are aggregated and representative emergy indices are calculated are shown in Table 2-6.

Table 2-6: Basic emergy flows and indices

Name	Units	Calculation
Basic emergy flows		
Domestic renewable input	sej	R
Domestic nonrenewable input	sej	N
Imported resources and services	sej	F
Exported resources and services	sej	EXP
Basic emergy indices		
Total Emergy Used (U)	sej	U = R + N + F
Imports to Exports	-	F / EXP
Emergy Investment Ratio (EIR)	-	EIR = F / (R+N)
Environmental Loading Ratio (ELR)	-	ELR = (F+N) / R
Emergy Yield Ratio (old EYR now LEI for territories)	-	EYR= LEI = U / F
Regional Emergy Yield Ratio (REYR)	-	EYR = EXP / F
Emergy Sustainability Index (EmSI)	-	EmSI = EYR / ELR
Indigenous fraction	%	(N+R) / U
Renewable fraction	%	R / U

Source: D. E. Campbell and Garmestani (2012); Center for Environmental Policy (2009).

2.2 Pros and Cons of Emergy Analysis

Emergy (with an "m") is a very effective energy accounting method for addressing two out of the three major issues in South Korea's conventional energy accounting system as was pointed out in the problem statement. They are (1) insufficient information about how energy use is related to society and the environment in the country and (2) non-compliance with thermodynamic principles. However, it suffers its own shortcomings, too. In this section, the advantages and shortcomings of emergy analysis are explained.

2.2.1 Advantage of emergy compared to the conventional energy accounting system

2.2.1.1 More information about how energy production and consumption is related to the society and environment of the country

When a complex consisting of the energy system, society, and the environment is studied, it is understood better by looking at the whole picture rather than analyzing each part separately. "A system is more than sum of its parts" (Jørgensen, 2012, p. 261)[3]. In this regard, emergy accounting has merits.

First, emergy accounting shows the interaction between society and energy use. For society's contribution to energy, emergy takes into account human labor, societal services, and information. Those factors are rarely counted in the conventional energy accounting system. For example, if an energy source is used in a country, the energy source accompanies both the emergy in the source itself and the emergy of

[3] This idea is first suggested by J. C. Smuts. For example, he stated, "A whole, which is *more* than the sum of its parts, has something internal, some inwardness of structure and function, some specific inner relations, some internality of character or nature, which constitutes that *more*." (Smuts, 1927, p. 105)

labor and societal services that have been invested in mining, processing, and transporting (Odum, 1996). At the same time, emergy shows how energy contributes to society. With indicators like the Emergy Yield Ratio (EYR), emergy can better distinguish the contribution of energy to society compared to the conventional energy accounting system. In addition, a combined emergy and monetary measure called the "emdollar" (or EM$) can show the overall monetary flows in a national economy as they are tracking real wealth (i.e., emergy), although this approach is not thorough (Mori & Christodoulou, 2012). Emdollar is a measure of the emergy that circulates in an economy measured by prorated monetary units, e.g., dollars or won. In practice, to obtain the emdollar value of an emergy flow or storage, the emergy is divided by the ratio of total emergy to GDP for the national economy (Brown & Ulgiati, 2004).

Second, for the contribution of the environment to energy, emergy accounts for free services such as photosynthesis and dilution of pollutants by the wind. (Brown & Ulgiati, 2007). Emergy analysis pursues strong sustainability and includes external impacts. Here, strong sustainability regards natural resources as unsubstitutable, which assumes that natural resource loss is irreversible and that people don't know what will be the exact outcome of degradation or loss of natural resources. Because emergy analysis differentiates each energy and other natural resources by their qualities, it can be said that emergy supports strong sustainability. Strong sustainability is the opposite of weak sustainability, which assumes that natural resources are abundant or substitutable with man-made capital or human labor and resource constraints can be overcome by technical progress (Neumayer, 2010).

2.2.1.2 Compliance with thermodynamic principles

The conventional energy accounting system is captivated by the mathematical equations of neoclassical economics and cannot appropriately apply thermodynamic principles to national energy systems (Latouche, 2009). The emergy accounting system overcomes this limitation.

Emergy is called "a thermodynamic method from systems ecology" (Hau & Bakshi, 2004). Emergy follows principles of thermodynamics just as exergy methods do, and makes possible the aggregation of multiple resources in a scientifically rigorous manner. If the boundary of emergy analysis is restricted to industrial processes, emergy and exergy are directly comparable. But emergy goes beyond the boundary and includes the ecosystems so that it can analyze the thermodynamics of the entire human-environment system (Bakshi et al., 2011).

2.2.2 Weak points of emergy analysis as an alternative energy accounting method

2.2.2.1 Less used information on intragenerational equity

Intergenerational equity (Holden et al, 2014) can be indirectly assessed by emergy analysis. However, so far, emergy analysis has not used intragenerational equity properties very much (Gasparatos, El-Haram, & Horner, 2008).

2.2.2.2 Difficulties to develop a time series database

Due to its complex data requirements, emergy accounting shares a common problem with other related accounting methods such as Life Cycle Assessment. Emergy researchers have found that it is not easy to build a database spanning a long period of time such as a country emergy database with decades of data input (Mathew J. Cohen, Sweeney, King, Shepherd, & Brown, 2012; Ulgiati, Agostinho, et al., 2011).

Although the emergy analysis uses actual numerical values for analyzing a country's energy system, not all numbers are generated by one institution according to the same rigorous standards. There can be errors in some numbers or inconsistencies between statistics-issuing institutions. If multi-year data are required, the data manipulation becomes much more difficult. For this reason, many researchers only use data from a single year.

However, a certain year's emergy flows alone cannot tell us how energy or climate policies are working in a country, even if results from the latest research are used for the synthesis. This is why a time series analysis is essential for a national level energy system analysis like the emergy accounting performed in this study.

2.3 Equity Issues in Energy Accounting

Equity is an important part of a country's sustainability. When vulnerable people suffer from inadequate health service, unequal levels of education, biased political representation, etc. in a country, the significant inequity restricts the country's long-term sustainability (World Bank, 2005). The energy sector is not an exception. Equitable use of energy attained by its provision at affordable prices is a prerequisite for sustainability (Moss et al., 2012).

However, it is not easy to find studies on the relationship between household income and life cycle energy and material flows. The United Kingdom has contributed major studies on equity issues in residential energy consumption. This was the country which proposed the concept of "fuel poverty" and which has been refining its definition and measurement methods to identify vulnerable households more efficiently, in order to develop appropriate policies (Hills, 2012). In the UK, researchers have exploited survey data to identify which factors determine household energy consumption, and one of the recurring factors was household income (Meier et al., 2013).

Specifically, the Centre for Environmental Strategy in the University of Surrey carried out a comprehensive analysis of different income groups' energy consumption. They analyzed household energy consumption by final energy sources and the consequent CO_2 emissions by income quintile or decile (Druckman & Jackson, 2008; Papathanasopoulou & Jackson, 2009). However, they did not delve into more quantitative analysis of energy quality. Their studies did not count material flows, either.

In the United States, average consumption of different fuels (electricity, natural gas, propane/LPG, fuel oil, kerosene) in eight groups according to annual household income have been estimated in an energy unit (million Btu per household) in the U.S. Energy Information Administration's quadrennial Residential Energy Consumption Surveys (RECS) (EIA, 2012). But the data sets provide only heat equivalent energy values.

Household energy consumption by income groups in developing countries in Asia and Africa has also been analyzed by the World Bank (Bacon, Bhattacharya, & Kojima, 2010). Although the study did a more detailed analysis by separately surveying urban and rural households, the consumption of different energy sources was only expressed in monetary values, not by energy equivalents or material flows.

South Korea's inequality is higher than most developed countries, according to the UN's Human Development Report for the year 2014. South Korea ranked 15th in the world by the Human Development Index (HDI). However, the country's rank plummeted to 35th by the inequality-adjusted Human Development Index. This 20 levels drop is second only to that of the United States (from 5th by HDI rankings to 28th by inequality-adjusted HDI rankings) (UNDP, 2014). When income gap or income inequality is exacerbated in the future as predicted by recent studies (Osberg, 2014; Piketty, 2014), low income households in South Korea will be more adversely affected by the change than those in other developed countries.

Therefore, researchers in South Korea have also studied issues of energy poverty or fuel poverty. The Korea Energy Economics Institute (KEEI) tried to estimate the scale of Korea's energy poor households (Shin, 2011). Studies by the Institute for Climate Change Action (ICCA) analyzed low-income households' energy consumption (ICCA, 2009, 2011). Researchers at Seoul Development Institute conducted a similar analysis on low-income households in Seoul (Jin, Park, & Hwang, 2009). But no study has calculated energy and material flows in different income groups. Only the triennial energy consumption surveys by the KEEI have been tracking the quantified energy consumption changes in different income groups (KEEI, 2000, 2003, 2006, 2009, 2012a) and the survey is similar to the RECS in the United States. But the surveys still do not provide adequate information about flows of energy and materials.

2.4 Emergy Assessment of Countries, Sub-National Entities, and Cities

For a better understanding of the benefits of emergy accounting for national sustainability policy development, it is essential to review previous studies on national and sub-national entities. In this section, emergy studies on foreign governments and South Korean cases will be reviewed, respectively.

2.4.1 National emergy analysis

The Center for Environmental Policy at the University of Florida has developed a global database for country-by-country emergy evaluation, called the "National Environmental Accounting Database" or NEAD (Brown, Cohen, & Sweeney, 2009; Mathew J. Cohen et al., 2012; Lei & Zhou, 2012; Sweeney, Cohen, King, & Brown, 2007). For the years 2000, 2004, and 2008, various emergy flows can be compared between countries. The NEAD provides useful indices. For example, Brown et al. (2009) used the Emergy Yield Ratio (EYR) as an index of 'net energy' of energy sources. They also used the Emergy Sustainability Index (EmSI) for predicting sustainability of countries, implying that those countries with the highest exploitation level of the environmental resources have the lowest EmSIs. In addition, the carrying capacity for a country is defined by "the annual emergy income" of the country from renewable sources. However, some country-specific data in the NEAD are absent and inconsistencies in the gathering and aggregation of raw data and conversion factors have been criticized (Rugani, Huijbregts, Mutel, Bastianoni, & Hellweg, 2011).

Independent of the NEAD global emergy database, many scientists have been carrying out emergy analysis on various countries. Above all, emergy flows of the United States were extensively analyzed. Odum (1996, pp. 182-207) was the originator of these analyses. To show how emergy evaluation can give an appraisal of a country's sustainability, he calculated the storages and flows of emergy in the United States. Based on the emergy data, 21 basic emergy indicators were generated. To get a sense of the economic sustainability of the United States, Odum compared the emergy/money ratio (national emergy used per year divided by the GNP) of the United States with those of other countries.

Tilley (2006) conducted a time series emergy analysis over the span of 1790-2000. He tracked down the level of resource and energy consumption in the United States by calculating the emergy flows over the time period. He regarded the country as an ecological system and called the emergy flows "national metabolism." Tilley presented historical changes in the Environmental Loading Ratio (ELR; ratio of non-renewable to renewable emergy use), indicating a sharp rise of ELRs in recent years. Furthermore, he used the "per capita emergy use" of American people as a measure of living standard.

Campbell and Lu (2009) conducted emergy analysis on the United States over the period 1900-2007. This research stands out in two aspects. First, the authors tried to update UEVs using the latest data. Second, they compared the performance of the total emergy use and the total energy in interpreting the GDP changes over the period longer than one century. Especially, they demonstrated how the total emergy could better explain the GDP than the total energy does, when the economy undergoes structural changes (the domestic energy development boom since the 1974 oil embargo or the increased use of electricity ushered in by the information age) or suffers from speculative expansions (e.g., internet bubble and housing mortgage bubble).

There is an exergy accounting method that is very close to the emergy accounting. Ukidwe and Bakshi (Ukidwe, 2005; Ukidwe & Bakshi, 2007) calculated industry-specific exergy flows and made a nation-wide exergy analysis on the United States. The authors titled the approach "Ecological Cumulative Exergy Consumption" (abbreviated "ECEC"). Although their methods are slightly different from emergy evaluation, their emphasis on preciseness in applying the laws of thermodynamics should be noted.

Because China, the world's second largest economy, has evoked global concerns about its sustainability due to the country's fast economic growth and environmental degradation, the country has been intensively studied using emergy analysis. Especially, two time series studies of the country give an insight into national sustainability policy development.

Yang et al. (2010) carried out an emergy evaluation for the Chinese economy over the period of 1978-2005. Their results indicate that China's economic growth was dependent on the exploitation of non-renewable natural resources. They also found that the contribution of indigenous resources had been declining, while the share of imported non-renewable resources (fuels, metals, and foods) in the total emergy use had been increasing. When they looked at emergy synthesis indicators, they found that the emergy/money ratio had been decreasing, while the ELR had been increasing. They also found that "Emergy Self-support Ratio" or ESR, the percentage of indigenous renewable and nonrenewable emergy within the total national emergy use, had been gradually decreasing.

Lou and Ulgiati (2013) extended the time scope of Yang et al. (2010) until the year 2009. While reaffirming the findings of Yang et al. (2010), they found that the emergy sustainability index had been decreasing throughout the research period. They also suggested policy options for China's future sustainability. These include discarding quantitative growth, increasing the resource use efficiency, and pursuing equitable trade.

Some Chinese scientists have modified the emergy concept and developed their own unit called "embodied cosmic exergy" or "cosmic emergy" (G. Q. Chen, 2006; H. Chen, Chen, & Ji, 2010). However, their approach is thermodynamically different from Odum's original ideas and the two approaches cannot be easily compared with each other (Brown & Ulgiati, 2010).

In addition to the United States and China, researchers have analyzed emergy flows in Japan (Gasparatos & Gadda, 2009), the United Kingdom (Gasparatos, El-Haram, & Horner, 2009), Taiwan (Huang, Lee, & Chen, 2006), Denmark (Haden, 2003), Spain (Lomas, Álvarez, Rodríguez, & Montes, 2008), and Argentina (Ferreyra & Brown, 2007), to name a few.

Although Japan, the United Kingdom, and Taiwan are all island countries, the emergy evaluation studies of Japan (Gasparatos & Gadda, 2009) and Taiwan (Huang et al., 2006) with time series data provide more ideas for national sustainability policy development than the UK study (Gasparatos et al., 2009), which has only one year's data. After analyzing the emergy flows in Japan over the period of 1979-2003, Gasparatos and Gadda (2009) found that the shares of domestic renewable and non-renewable sources declined, while that of imported sources increased. In addition, they found a strong positive relationship ($R^2 = 0.97$) between the ELR and CO_2 emissions. Total emergy use also showed a positive relationship with nominal GDP ($R^2 = 0.84$). In the case of Taiwan, Huang et al. (2006) calculated material and energy flows by emergy accounting from 1981 to 2001. They found that emergy synthesis gives more insights than simple statistics on material or energy quantities.

For Denmark, Haden (2003) made emergy evaluations for the years 1936, 1970 and 1999, rather than building a time series emergy database. Because there were more than 60 years between the first and the last years, the study found more evident changes in emergy indicators. For example, the Emergy Sustainability Index (EmSI) decreased by more than 90%, and the Emergy Footprint Ratio (EFR; total emergy use divided by indigenous renewable resources) increased more than 5 times.

For the sustainability assessment of Spain, Lomas et al. (2008) conducted an emergy analysis of the years 1984, 1989, 1994, 2000 and 2002. They found a dramatic decline of the Emergy Sustainability Index (EmSI) during the studied time period, because the ELR kept increasing while the Emergy Yield Ratio slighted decreased.

Ferreyra and Brown (2007) used emergy accounting to assess changes in the ecological sustainability of the Argentine economy during the 20th century, using data from 1900 to 1995. Their findings are similar to other studies. Although total emergy use increased, the portion of the economy supported by renewable sources decreased. The ELR for Argentina doubled during the century. Because their study covered almost one century, they could detect changes in trends, too. They found the ratio of imports to exports (evaluated in emergy) had a positive trend in the early 20th century but had been decreasing since 1976.

2.4.2 Sub-national-level emergy analysis

In the United States, a number of states have had their emergy flows analyzed. Emergy flows in Florida were calculated by Odum and his colleagues (Odum, Odum, & Brown, 1997). The emergy flows of Maine were also computed (D. E. Campbell, 1998). Recently, the United States Environmental Protection Agency (EPA) has published emergy analysis results on West Virginia (D. E. Campbell, Brandt-Williams, & Meisch, 2005) and Minnesota (D. E. Campbell & Ohrt, 2009).

For Florida, Odum et al. (1997) carried out a comprehensive emergy evaluation. First, to help readers understand how the environment and society are interacting with each other; they drew system diagrams for ecosystems (coral reef system, estuaries, freshwater ecosystem, wetlands, forests, etc.) and industries (agriculture, fisheries, tourism, etc.). Second, they conducted an emergy synthesis for Florida. They found that only 15% of Florida's population can continue their living standards with Florida's carrying capacity at that time. They also calculated the Emergy Investment Ratio (EIR; the ratio of the emergy of purchased inputs to that of renewable resources) and the emergy/money ratio and found that the state had been highly urbanized and become dependent upon resources from the outside. Third, they developed a stylized computer simulation model for the economy of Florida. Although their assumption was relatively simple, the model simulation clearly showed how resource constraints affected a state's future sustainability in association with trade.

For Maine, Campbell (1998) performed an emergy analysis for the year 1980. He compared emergy indices of Maine with those of other states and the whole country. He found Maine's carrying capacity was 34% of its population. Although it was significantly higher than that of the U.S. average, which was 10% of the national population in 1983, Campbell concluded that either the population size or the rate of resource consumption (i.e., a standard of living as measured by emergy use per person) had to be decreased in order to achieve long-term sustainability.

The two studies by the U.S. EPA (D. E. Campbell, Brandt-Williams, & Meisch, 2005; D. E. Campbell & Ohrt, 2009) compare West Virginia and Minnesota with their emergy synthesis results for 1997 and 2000. The comparison shows us how future development direction can be inferred for a state using the information about the EIRs and the ELRs. Two states' small carrying capacities and low emergy self-sufficiency indices (the ratio of the emergy use from home sources) are clear evidence that revolutionary solutions are urgently needed for the sustainable development of a nation or a sub-national entity. Imports and exports of emergy between states and the overall nation show us how a national development policy should be implemented to ensure equitable development between different sub-national entities. Although a complete 50-state emergy database could have been a very effective tool for promoting and enhancing sustainability policies rather than this two-state comparison, the EPA studies laid a platform for collecting data and building a database that is consistent among different states.

In Italy, a study performed emergy analysis on the Abruzzo region, which is an equivalent of a state in the U.S. Pulselli (2010) applied emergy accounting to geographic information systems for the Abruzzo region in Italy. He collected raw data from four provinces and 315 municipalities in Abruzzo. Because the region is divided into 315 sub-regions, Pulselli could map the spatial changes of emergy intensity over the studied area. This GIS approach could refine a national energy and environmental policy in order to be customized for more localized needs.

In China, time series emergy flows of the autonomous region of Inner Mongolia were analyzed. Zhu et al. (2012) conducted emergy evaluations on Inner Mongolia, China over the period of 1987–2007. They found that the region's emergy use from indigenous sources (emergy self-sufficiency indices) was over 84%. Especially, they used a ternary diagram in association with Emergy Sustainability Indices (EmSIs). The ternary diagram (Giannetti, Barrella, & Almeida, 2006) that consisted of indigenous renewable sources, indigenous nonrenewable sources, and imported resources depicted how the resource structure of the region changed over time. Because the EmSI is the ratio of EYR to ELR, a few rare combinations of EYR and ELR values could give wrong information about a region's sustainability (Giannetti, Almeida, & Bonilla, 2012). However, their ternary diagram provided additional information and reduced the confusion.

2.4.3 Emergy analysis of megacities

Efforts to apply emergy analysis in cities can be found in the cases of Rome (Ascione, Bargigli, Campanella, & Ulgiati, 2011; Ascione, Campanella, Cherubini, & Ulgiati, 2009), Beijing (Liu, Yang, Chen, & Ulgiati, 2009, 2011; Liu, Yang, Chen, & Zhang, 2011; Su et al., 2011; Y. Zhang, Yang, Liu, & Yu, 2011), megacities in China (Cai, Zhang, Zhang, & Chen, 2009; L. X. Zhang et al., 2009), and Taipei, Taiwan (Huang & Chen, 2009). For Rome, the same research group published two papers. Ascione et al. (2009) compared the emergy synthesis results for Rome with data from 2002 with those of other international cities such as Taipei, Macao, and San Juan (Puerto Rico). They found that emergy intensity indicators including 'emergy per capita', 'empower density', and 'emergy/money ratio' are more effective than other emergy indices, when cities with different backgrounds are compared. Meanwhile, Ascione et al. (2011) analyzed emergy flows in Rome from 1962 to 2002. However, in this paper, they considered emergy as just one indicator of Rome's demand for the natural environmental support. All of these inputs would be part of a complete emery analysis of the city. Then, in order to get intensities of those factors' consumption or depletion, they divided all those variables by the population, GDP, and land area of Rome. They concluded that the multi-dimensional study would reduce the possibility of misunderstanding a city's real state of sustainability.

Beijing is arguably the most studied city in the world by emergy scientists. The paper by Zhang et al. (2011) is a time series emergy evaluation of Beijing over the period 1990 to 2004. They computed basic emergy indices such as ESR (Emergy Self-support/sufficiency Ratio), ELR, ED (Empower Density), EDO (emergy/money ratio), and EP (emergy use per person). The temporal changes of the indices gave an insight into how Beijing had been affected by fast development.

Cai et al. (2009) compared Beijing with two neighboring mega cities (Tianjin and Tangshan) using a time series emergy evaluation over 1990-2006. They compared three cities with basic emergy indices. A unique approach in the study is that they computed the ratio of total waste to total emergy use and used the results as an indicator of the environmental pressure of pollutions. Zhang et al. (2009) used almost the same methods for comparing Beijing with Shanghai and Guangzhou.

Liu et al. (2009) compared the emergy flows of Beijing with those of 30 cities in China. For a better comparison of the cities, they introduced a new urban ecosystem sustainability index in two steps. First, they adopted the emergy-based index of sustainable development (EISD), a modified version of the Emergy Sustainability Index (EmSI), as Lu, Ye, Zhao, and Peng (2003) suggested. It is expressed as an equation, $\mathrm{EISD} = \mathrm{NEYR} \times \frac{EER}{ELR}$, where the NEYR is the net emergy yield ratio, the EER is the emergy exchange ratio, and the ELR is the environmental loading ratio. Second, they created the emergy-based urban ecosystem health index (EUEHI). It is calculated by an equation, $\mathrm{EUEHI} = \frac{NEYR \times EER \times ED}{ELR \times EMR}$, where the ED is the emergy density and the EMR is the emergy/money ratio. After generating the emergy indices, they compared cities with NEYR, EER, ELR, ED, and EUEHI. Finally, according to similar EUEHI values, cities could be grouped into 6 clusters. Although their approach is very convincing, the EUEHI is not easy to understand, because it is a composite of five already synthetic indices. That could be a reason that a similar composite emergy index (UEHI, Urban Ecosystem Health Index) in a time series study of Beijing over 1986 to 2005 (Su et al., 2011) didn't show a discernible trend over time while most of the UEHI's components had monotonic changes during the period.

Mostly the same group of researchers (Liu, Yang, Chen, & Ulgiati, 2011; Liu, Yang, Chen, & Zhang, 2011) as Liu et al. (2009) conducted a time series emergy evaluation of Beijing over the years 1999-2006. In addition to the basic emergy synthesis, they calculated human and natural capital losses due to airborne- and waterborne-pollution. Although the authors acknowledged the large uncertainties especially in estimation of natural and human capital losses caused by pollution, this study shows an example of emergy accounting's broad applicability.

For Taipei, the capital city of Taiwan, Huang and Chen (2009) performed an emergy synthesis of the city's socioeconomic metabolism from 1981 to 2002. Using remote sensing data, they divided Taipei into undeveloped (forested), agricultural, and urban areas. Because they examined both land use and emergy indices, they showed how a predominant direction of development (in this case, urbanization) affected spatial changes in environmental resources. In addition, they reaffirmed a dire unsustainability of typical megacities using Taipei's extremely low Emergy Sustainability Indices (EmSIs).

2.5 Emergy Application in South Korea

2.5.1 National emergy analysis

Lee and Odum (1994) conducted the first emergy evaluation of South Korea, using 1991 data. According to their emergy synthesis results, South Korea's carrying capacity could support only 3.32 million people out of a total population of 43.3 million. They also compared South Korea with other countries by emergy use per person, emergy self-sufficiency index, and emergy import/export ratio. As an exemplary emergy evaluation of South Korea, this study showed the overall state of South Korea's energy flows in the economic and life support systems.

Since then, many Korean researchers have undertaken emergy evaluations with newer data. Notable studies are by Kang and Nam (2003) using 1999 data, J. Y. Choi, Jeon, Park, and Yoon (2004) using 2003 data, and Nam and Lee (2010) using 2008 data. These studies calculated emergy indices such as human carrying capacity, EYR, ELR, and EmSI (emergy sustainability index).

The Center for Environmental Policy in the University of Florida conducted their own emergy analysis on South Korea, too. Although some key data were missing in their database, because they used only internationally comparable data, the Center for Environmental Policy has analyzed the emergy flows of South Korea using 2000, 2004, 2008 data (Center for Environmental Policy, 2009; Sweeney et al., 2007).

However, it is not easy to compare the results from all these disparate research papers. Their emergy synthesis results are not easily comparable with each other, as the following table exhibits. Especially, the total emergy inflows in the same year of 2008 calculated by the Center for Environmental Policy (3.28×10^{24} sej/yr) and Nam & Lee (1.83×10^{24} sej/yr) show a significant difference. It is not because either or all of their analyses were incorrect. It is because different authors used different data collection and conversion methods. How to avoid 'double counting' in total renewable emergy flow estimation is another reason (D. E. Campbell, Brandt-Williams, & Cai, 2005). These methodological discrepancies are the reason why a time series database using consistent principles in data processing is required for a reliable policy impact analysis.

Table 2-7: Emergy inflows in South Korea calculated by different studies

Data year	Emergy inflows (sej/yr)				Reference
	Domestic renewable flows	Domestic nonrenewable sources	Imports	Total	
1990	3.29E+22	1.21E+22	3.84E+23	4.29E+23	Lee and Odum (1994)
1999	5.14E+22	8.95E+22	9.21E+23	1.06E+24	Kang and Nam (2003)
2000	1.52E+23	4.56E+23	1.92E+24	2.53E+24	CEP (2009)
2003	1.02E+23	2.67E+23	7.27E+23	1.10E+24	J. Y. Choi et al. (2004)
2004	1.52E+23	5.56E+23	2.01E+24	2.71E+24	CEP (2009)
2008	1.52E+23	5.44E+23	2.59E+24	3.28E+24	CEP (2009)
2008	3.24E+23	1.01E+23	1.41E+24	1.83E+24	Nam and Lee (2010)

Note. Numbers are expressed relative to the 9.26E+24 sej/yr planetary baseline.

2.5.2 Sub-national- and city-level emergy analysis

In South Korea, sub-national level emergy analyses have been carried out for Seoul (C.-W. Lee & Oh, 1999), Busan (Yu, 2006), Daegu (W.-S. Lee, Jung, & You, 2005), and Jeollabuk-do province (B.-G. Kim, Lee, & Lee, 2005). For their study area, researchers calculated basic emergy indices such as emergy use per person, EIR, EYR, ELR, and EmSI (EYR/ELR). But none of them performed a time series emergy evaluation and it was difficult to compare emergy indices between those areas due to their different data collection and processing methods.

2.6 Theoretical Framework

The United Nation's World Commission on Environment and Development (1983-1987; WCED) was a definitive starting point for the present global sustainability discourse. The final report of the WCED, "*Our Common Future*" (sometimes called "*The Brundtland Report*" after the name of the commission chair), defined sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987).

In this study, the WCED's definition of sustainability is modified to a sustainability framework to serve the purpose of this study. In order to explain how well a society is doing quantitatively and qualitatively, it is useful to choose principal themes constituting sustainability. For example, the United Nation's World Summit on Sustainable Development (WSSD) (2002) identified three pillars (economic development, social development and environmental protection) of sustainable development. Nurse (2006) asserted there are four dimensions of sustainability: social justice, ecological balance, self-reliance, and cultural identity. Seghezzo (2009) went further by combining five dimensions (three spatial, one temporal, and one human dimensions) to help policymakers visualize the concept of sustainability.

This study uses a four-element theoretical framework to explain sustainability. The four elements are energy, economy, the environment, and equity. This "E4 framework" is almost identical with that of Wang, Byrne, Boo, Yun, and Soh (1996). Wang et al. extracted four "E"s from the overview section of "*Our Common Future*", cited as “sustainable development is not a fixed state of harmony, but rather a process of change in which the exploitation of resources (*energy*), the direction of investments (*economy*), the orientation of technological development (*environment*), and institutional change (*socio-politics: equity*) are made consistent with future as well as present needs.” (WCED, 1987) (The italic words in the parentheses are inserted by Wang et al. (1996, p. 5).) This close relation between the four elements is reaffirmed by a coeditor of the World Energy Assessment (UNDP, 2004), who said:

> “The linkages between *energy* systems and *economic development*, *social equity*, and *environmental protection* described thus far indicate that a change in present energy system development is required if sustainable development pathways are to be realized.” (Johansson, 2005, p. 49)

Energy makes it possible for the economy to function, while economy provides goods and services to the energy sector. The environment provides renewable and non-renewable energy sources, when the energy sector affects the environment in the supply and consumption of energy. The energy sector affects the equity of the resource distribution among people.

As explained in the previous section, the conventional energy accounting system is concentrated mostly on energy, and does not properly deal with economy, the environment, and equity. In contrast, emergy analysis already addresses three of the four elements of sustainability and can be further developed to address the fourth. The only element that is not currently addressed in emergy analysis is equity. If equity data are integrated with emergy analysis, the sustainability of a country can be assessed by all four indicators.

Due to the intertwined nature of elements in E4 framework, any indices or indicators do not exclusively belong to a certain element. In this study, however, they were categorized into one of the E4 framework elements by the following standards.

Firstly, if the indices or indicators are related to the GDP or international trades, they are grouped into the 'economy' element. The indices or indicators are: 1) shares of total energy/emergy use to GDP, 2) economic efficiency of energy/emergy use, 3) trades of resources, and 4) relationship between imports and domestic resources.

Secondly, if the indices or indicators are mainly dealing with conventional energy use, they are identified as part of the 'energy' element. The indices or indicators include: 1) energy supply in energy/emergy terms, 2) final energy consumption in energy/emergy terms, and 3) energy sources of electricity in energy/emergy terms.

Thirdly, if the indices or indicators are mainly dealing with environmental burdens or material consumption, they are categorized into the 'environment' element. The indices or indicators include: 1) carbon dioxide emissions relative to energy/emergy use, 2) material demand in conventional/emergy accounting, 3) air pollution in conventional/emergy accounting, and 4) environmental burden in conventional/emergy accounting.

Finally, if the indices or indicators are dealing with intragenerational equity or intergenerational equity, they are categorized into the 'equity' element. The indices or indicators include: 1) intragenerational equity measured by energy/emergy-related Gini coefficients and 2) intergenerational equity measured by shares of renewable energy in energy/emergy terms.

After the classification, the indices and indicators synthesized from the E4-Emergy evaluation results are compared with key well-known sustainability indicators that are produced from conventional energy accounting methods. If there is not a comparable counterpart from conventional energy accounting methods, the unique aspects of such emergy indices or indicators will be discussed.

In addition, to better understand South Korea's sustainability in the global context, 9 countries with published comparable emergy evaluation studies were selected and their data were compared with results of this study. The countries are: Brazil (Pereira & Ortega, 2013), China (Lou & Ulgiati, 2013), Denmark (Haden, 2003), Japan (Gasparatos & Gadda, 2009), Portugal (Oliveira, Martins, Gonçalves, & Veiga, 2013), Spain (Lomas et al., 2008), Taiwan (Huang et al., 2006), United Kingdom (Gasparatos et al., 2009), and United States (D. E. Campbell, Lu, & Walker, 2014). Henceforth, if any figure or table is produced using the data from the 10-country comparison, Table A-11 in the appendix will be referred to instead of citing all the nine papers each time. Table A-11 is a summary list of 9 references.

The following figure represents the conceptual framework of this study. The tetrahedral shape is suggested by O'Connor (2006).

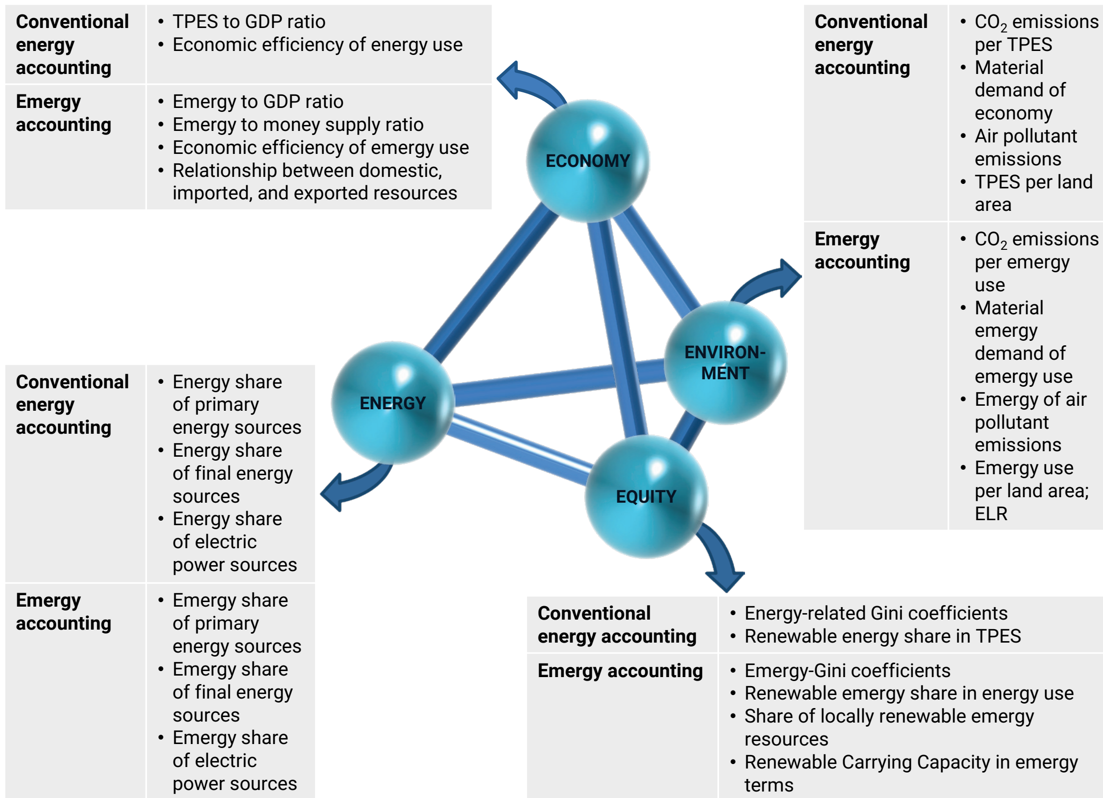


Figure 2-3: E4 sustainability framework: comparison of the conventional energy accounting and emergy accounting systems.

Chapter 3

DATA AND METHODOLOGY: E4-EMERGY EVALUATION

In this chapter, how the E4-Emergy evaluation was conducted over the period 1998-2010 is explained. It consists of raw data collection, Unit Emergy Values collection, basic emergy analysis, equity data collection, time series E4-Emergy database development, and emergy-equity analysis.

3.1 Raw Data Collection on Energy and Material Storage and Flows

Before conversion to emergy, raw data for energy and material flows in and out of South Korea were collected. The four sources of energy and material flows are domestic renewable energy, domestic non-renewable resources, imports, and exports. Methods of raw data collection followed those of Nam and Lee (2010), with a few modifications. Domestic renewable energy sources consist of solar, wind, rain, wave, deep heat, and tidal energy. Energy and material flows in domestic non-renewable resources account for the available energy embodied in coal production, metallic and nonmetallic minerals production, and topsoil loss.

Energy and material flows in imports and exports are calculated for both imports and exports of fuels (anthracite and bituminous coal, crude oil, petroleum products, natural gas, uranium), metallic minerals, nonmetallic minerals, metal products, cements, food and agricultural products, livestock/meat/fish, plastics and rubber, chemicals, finished materials (leather products, lumber & wood products, paper, textiles, glass & ceramics, others), machinery and transportation equipment, and import/export services.

Data sources for each energy/material flow calculation are summarized in Table 3-1.

Table 3-1: Raw data sources for emergy database development

Energy and material sources		Required data	Source
Domestic renewable energy sources		Land area	(MLTM, 2012)
		Insolation	(KMA, 2012d)
		Continental shelf area	(MOF, 2013)
		Average wind speed	(KMA, 2012a)
		Rain	(KMA, 2012c)
		Mean tidal range	(MOE & NIER, 2012)
		Total inland area	(MLTM, 2012)
		Elevation	(D. Kang & Nam, 2003)
		Coastline lengths	(Ryu, Hong, Shin, Kim, & Kim, 2011)
Domestic non-renewable sources		Coal (anthracite) production	(KEEI, 2011)
		Natural gas production	(KEEI, 2011)
		Metallic ores & concentrates production	(KIGAM, 2012)
		Nonmetallic minerals production	
Sources from imports and exports	Imports only	Oil (crude)	(KEEI, 2011)
		Natural gas (LNG)	
		Bituminous (for steam)	
		Bituminous (for iron & steel)	
		Anthracite	
		Uranium	
	Imports and exports	Petroleum products	(KEEI, 2011)
		Metallic ores & concentrates	(KIGAM, 2012)
		Nonmetallic minerals	
		Metal products	(KCS, 2012a)
		Cements	
		Food and agricultural products	
		Livestock, meat, & fish	
		Plastic and rubber	
		Chemicals	
		Chemicals (excluding fertilizers)	
		Chemicals (fertilizers)	
		Finished materials - Leather products	
		Finished materials - Lumber & wood products	
		Finished materials - Paper	
		Finished materials - Textile	
		Finished materials - Glass & ceramics	
		Finished materials - Others	
		Machinery & transportation	
		Service in imports and exports	(KCS, 2012b)

3.2 Parameters (Unit Emergy Values) Collection

To calculate the emergy of all energy and material flows in and out of South Korea, Unit Emergy Values (UEVs) are required. In this study, UEVs are collected from various sources that are already published. Currently, four main sources of the UEVs are Nam and Lee (2010), Tilley et al. (2012), Campbell and Ohrt (2009), and Campbell and Garmestani (2012). However, some of the given values are improved with more accurate data.

3.3 Basic Emergy Analysis of South Korea

Basically, emergy analysis of South Korea is performed as explained in the previous section (2.1.5). In this section, it is explained in detail how each step of the evaluation was conducted.

3.3.1 Drawing a systems diagram

First, a systems diagram of all inflows and outflows in South Korea is drawn. Microsoft Office Visio 2015 is used to draw the diagram. An example of the task is Figure 4-1.

3.3.2 Building data tables for annual emergy flows

Second, tables of the actual flows of materials, labor (human resources), money, and energy are constructed. Line numbers are according to Table 2-5. Unless noted otherwise, all the basic equations are according to Odum (1996).

3.3.2.1 **Annual insolation** (Line #1 in Table 2-5)

Annual insolation data are from the average of 'total horizontal insolation' values measured at 22 sites spread over South Korea. The constant value 0.3 is an approximation of the average terrestrial albedo (0.297) as estimated by Goode et al. (2001). After the data preparation, the following formula was used.

Solar energy (J) = [Area of land and continental shelf] × [Average insolation] × [1−albedo]

3.3.2.2 **Wind emergy** (Line #2 in Table 2-5)

Wind data are revised. About 70% of the Korean Peninsula is covered by mountains and hills (NGII, 2010). So the lower drag coefficient 0.002 was assigned to 30% of the total land area and the higher coefficient 0.003 was assigned to the remaining 70% (Garratt, 1977). After the data processing, the following formula was used.

Wind energy (J) = ([Air density] × [Higher drag coefficient] × [Geostrophic wind]^3 × [3600×24×365] × [Area of mountains and hills]) + ([Air density] × [Lower drag coefficient] × [Geostrophic wind]^3 × [3600×24×365] × [Area of the remaining region])

3.3.2.3 **Rain emergy** (Lines #3-6 in Table 2-5)

For the four streams of rain emergy, the following formulae were used. Evapotranspiration is the sum of plants' transpiration and evaporation of water from the land surface. In Korea, the evapotranspiration rate is 42%. Consequently, the runoff rate is 58% (MLTM, 2011). Therefore,

a. Rain, chemical (land) (J) = [Land area] × [Rain] × [Evapotranspiration] × [1000 kg/m^3] × [4695 J/kg]

b. Rain, chemical (shelf) (J) = [Shelf area] × [Rain] × [1000 kg/m^3] × [4940 J/kg]

c. Runoff, chemical (J) = [Land area] × [Rainfall] × [Runoff] × [1000 kg/m^3] × [4940 J/kg]

d. Runoff, geopotential (J) = [Land area] × [Rainfall] × [Runoff] × [1000 kg/m^3] × [Average elevation] × [9.8 m/s^2]

For lines #3–5, Gibbs free energy values were recalculated using South Korea's measurement data for the surface air temperature (KMA, 2011) and the river water temperature (MOE, 2014b). The equation for calculating Gibbs free energy (G) is given as:

$$\mathrm{G} = \frac{RT}{w} \times \ln \frac{C_2}{C_1}$$

Where,

R = 8.3144621 J/mol/K, the universal gas constant (molar gas constant),

$T_{\_Surface}$ = 285.603379 K, annual average surface air temperature,

$T_{\_River}$ = 288.6771686 K, river water temperature

w = 18.01528 g/mol, molecular weight of water,

C_1 = 965000 ppm, concentration of dissolved solids in sea water, and

C_{2_Rain} = 999990 ppm, concentration of dissolved solids in rain water (Odum, 1996)

C_{2_River} = 999623 ppm, concentration of dissolved solids in river water.

Therefore, the Gibbs free energy of rainfall water in South Korea is

$\mathrm{G}_{\_Rain}$ = 4.694787986 J/g, and

the Gibbs free energy of river water in South Korea is

$\mathrm{G}_{\_River}$ = 4.696436549 J/g.

In addition, the average elevation of South Korea is 262 meters, according to Kang & Nam (2003).

3.3.2.4 **Wave energy** (Line #7 in Table 2-5)

Wave energy is calculated based on the following formula. The ocean waves absorbed at the shore is:

Wave energy (J)

= [shore length] × [1/8] × [density] × [gravity] × [height squared] × [velocity] × 3600 × 24 × 365 [sec/yr]

= [m] × [1/8] × [1025 kg/m^3] × [9.8 m/sec^2] × [m]^2 × [m/s] × 3600 × 24 × 365 [seconds/yr]

Although annual emergy inflows can be calculated by the equation, this study adopted wave energy estimates by the researchers from the Korea Ocean Research & Development Institute (KORDI). KORDI is currently a part of the Korea Institute of Ocean Science & Technology or KIOST (Ryu et al., 2011).

Above all, they re-estimated the length of Korea's coastline. South Korea's official coastline length is 12,803 km (KHOA, 2012). However, the number is very ambiguous. Due to the fractal nature of coastlines, there can be infinite number of drastically different estimates depending on underlying assumptions. For example, according to the CIA's World Factbook, South Korea's shoreline is 2,413 km long (CIA, 2012). Korea's official length is more than 5 times the CIA estimate as the two sources used different methods. Because the KORDI researchers were also aware of the fractal geometry of coastlines, they calculated the coastline length as the sum of connected straight lines each of which was drawn as a tangent line touching outermost shorelines in 18×18 km grids. The result is 1614 km (Ryu et al., 2011). Although it is only 12.6% of the official measurement of South Korean coastline length (12803 km), the recalculated value is more acceptable in wave energy assessment.

Then the KORDI/KIOST team calculated the potential wave energy resources by multiplying the estimated coastline length by wave energy density (kW/m). The wave energy density is based on hourly wave measurement records around South Korean shorelines maintained by the KORDI over 25 years (1979–2003). And their estimates for annual wave energy absorbed by 1614 km of South Korean coastlines is 87,412.3 GWh, which can be converted into 3.15E+17 J.

3.3.2.5 **Earth cycle energy** (Line #8 in Table 2-5)

For the Earth cycle energy, the latest measurement data for Korea's deep heat flow was used. According to Kim and Lee (2007), the mean heat flow of the Republic of Korea is 60 ± 11 milliwatts per square meter (mW/m^2). Because 1 Watt equals 1 J/s, $60 \times 0.001 \times 3600 \times 24 \times 365 = 1892160$. Therefore, the average deep heat flow is about 1.89E+6 J/m^2/yr.

3.3.2.6 **Tidal energy** (Line #9 in Table 2-5)

Tidal energy is recalculated. To do so, the mean tidal range of South Korean shores had to be determined by using actual measurement data.

Out of 219 tide measurement points selected by the Ministry of Environment, 66 non-island points were selected (MOE & NIER, 2012). Their locations begin from a northern-most end of eastern sea shores, go down to southern coasts, move to Yellow Sea (western sea) shores, and end at a northernmost part of western coasts (Table A-8 in the Appendix).

The mean tidal ranges of each point were calculated by averaging their spring ranges and neap ranges. Then the distances between the nearest two points were calculated using their geographic coordinates. When the area of a trapezoid between two points is computed, an average tidal range could be gotten. Finally, the distances and trapezoid areas throughout all the non-island measurement points were computed.

The sum of the distances between the 66 points was 1,288 km. The sum of the areas of trapezoids between the points was 2,935,304 m^2. By dividing the total trapezoid area by the total distance, the mean tidal range is estimated to be 2.279 meters. Then the tidal energy is 1.262E+18 J/yr (See Table A-8 in the Appendix.).

3.3.2.7 **Topsoil loss** (Line #12 in Table 2-5)

Topsoil loss is also calculated as Odum (1996). The organic matter content of soils (20 g/kg) and its calorific value (5.4 kcal/g) are from J. Y. Choi et al. (2004).

Energy (J) = [soil loss, g/yr] × [0.02 g organic matter/g soil] × [5.4 kcal/g] × [4186 J/kcal]

For the annual soil loss, it was assumed that the topsoil loss over the entire country is occurring at the same rate as that in the four major river watersheds calculated by Park, Oh, Jeon, Jung, and Choi (2011), because those watersheds already cover about 97% of the country.

3.3.2.8 **Fuels and commodities** (Lines #13–14, #17-a–f, #20–27, #29, #32–39 in Table 2-5)

For each item of fuels (excluding uranium, which will be explained in section 3.3.2.10) and commodities, specific UEVs were applied as cited in Table 2-5. Annual production, consumption, or traded quantities of the fuels and commodities are multiplied by their unique UEVs.

3.3.2.9 **Minerals: metallic and nonmetallic** (Lines #15–16, #18–19, #30–31 in Table 2-5)

Weighted UEVs were estimated for metallic and non-metallic minerals. After individual minerals' emergy values were computed by multiplying each mineral's production by their transformities (D. E. Campbell, Lu, & Lin, 2014), the sum of the mineral emergy was divided by the total weight of their production. The same process was applied to the metallic and non-metallic mineral groups.

3.3.2.10 **Uranium** (Line #17-g in Table 2-5)

During the study period of 1998-2010, there were 20 nuclear reactors (17.716 GW) operating in Korea. Among them, 4 Pressurized Heavy Water Reactors (PHWR; 2779 MW) consumed natural uranium fuels (0.711 % ^{235}U) and 16 Pressurized Water Reactors (PWR; 14937 MW) consumed low-enriched uranium fuels (approximately 4.5 % ^{235}U; to achieve a discharge burnup of 45 GWd/tonne U).

South Korea has no enrichment facilities. This means that Korea's annual uranium imports are a mixture of natural uranium fuels and low-enriched fuels. Korea imported natural uranium fuels for PHWRs and low-enriched fuels for PWRs. However, the total amount of uranium imports didn't distinguish how much is from natural or low-enriched uranium fuels.

So the total uranium imports were decomposed into natural and enriched fuels, which would give estimates of the exergy of annual uranium imports. For the decomposition, the annualized nuclear fuel requirements from each nuclear reactor in South Korea jointly estimated by the Korean government and the Korea Hydro & Nuclear Power were used (MKE & KHNP, 2008). Because the fuel requirements have already taken account of fuel rod replacement cycles, the 3.5-5 years' fuel burn-up time (C. H. Kim, 2009; PECOS, 2014) is already taken into consideration. In addition, the government report even provided the equivalent weights of natural U_3O_8 for each reactor's fuel requirements (MKE & KHNP, 2008).

Table 3-2: Emergy of uranium imports, 1998–2010

Year	Uranium imports (natural + enriched)	Equivalent weight of natural U_3O_8	Energy content of imported uranium		Emergy of uranium imports
	tonne U	tonne U_3O_8	GWh	Joule	sej
1998	844	3,663	162,740	1.60E+18	7.80E+22
1999	612	2,656	118,006	1.20E+18	5.70E+22
2000	576	2,500	111,064	1.10E+18	5.40E+22
2001	723	3,138	139,409	1.40E+18	6.70E+22
2002	778	3,376	150,014	1.50E+18	7.20E+22
2003	750	3,255	144,615	1.50E+18	7.00E+22
2004	808	3,507	155,799	1.60E+18	7.50E+22
2005	714	3,099	137,674	1.40E+18	6.60E+22
2006	737	3,198	142,108	1.40E+18	6.90E+22
2007	823	3,572	158,691	1.60E+18	7.70E+22
2008	883	3,832	170,260	1.70E+18	8.20E+22
2009	913	3,962	176,045	1.80E+18	8.50E+22
2010	824	3,576	158,884	1.60E+18	7.70E+22

Data source: MKE and KHNP (2008).

According to the data, it is estimated that Korea had to import 4.340 tonnes of natural U_3O_8-equivalent uranium to get one tonne of the mixed uranium fuels annually. Therefore, each year's nuclear power generation could be divided by each year's natural U_3O_8-equivalent fuel requirements.

Over the 1998-2010 period, one tonne of natural U_3O_8-equivalent mixed uranium fuels generated 44,430 MWh on average. In Korea, the average energy conversion factor for electricity was 10,016,114 J/kWh (GIR, 2014). Finally, the transformity of nuclear electricity is 4.81E+04 sej/J (D. E. Campbell & Ohrt, 2009). The results are summarized in Table 3-2.

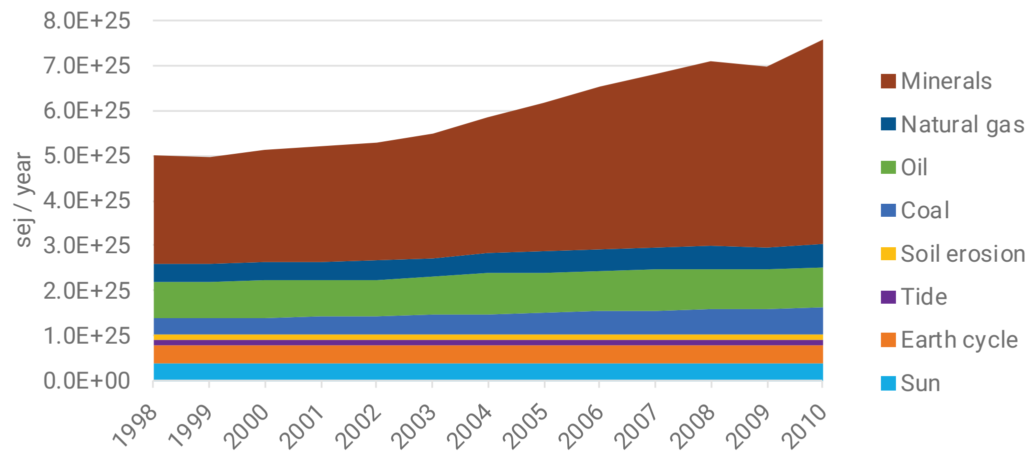
Table 3-3: Components of global emergy flows (sej/yr)

Year	Renewable sources			Nonrenewable sources from within system					Total emergy flows
					Nonrenewable resource production				
	Sun	Earth cycle	Tide	Soil erosion	Coal	Oil	Natural gas	Minerals	
1998	3.93E+24	4.07E+24	1.26E+24	1.06E+24	3.72E+24	8.06E+24	3.73E+24	2.40E+25	4.99E+25
1999	3.93E+24	4.07E+24	1.26E+24	1.06E+24	3.72E+24	7.91E+24	3.83E+24	2.41E+25	4.98E+25
2000	3.93E+24	4.07E+24	1.26E+24	1.06E+24	3.75E+24	8.22E+24	3.96E+24	2.50E+25	5.13E+25
2001	3.93E+24	4.07E+24	1.26E+24	1.06E+24	3.92E+24	8.22E+24	4.08E+24	2.54E+25	5.20E+25
2002	3.93E+24	4.07E+24	1.26E+24	1.06E+24	3.94E+24	8.18E+24	4.16E+24	2.61E+25	5.27E+25
2003	3.93E+24	4.07E+24	1.26E+24	1.06E+24	4.22E+24	8.48E+24	4.31E+24	2.75E+25	5.48E+25
2004	3.93E+24	4.07E+24	1.26E+24	1.06E+24	4.57E+24	8.87E+24	4.44E+24	3.04E+25	5.86E+25
2005	3.93E+24	4.07E+24	1.26E+24	1.06E+24	4.83E+24	8.96E+24	4.57E+24	3.32E+25	6.19E+25
2006	3.93E+24	4.07E+24	1.26E+24	1.06E+24	5.09E+24	9.01E+24	4.74E+24	3.62E+25	6.54E+25
2007	3.93E+24	4.07E+24	1.26E+24	1.06E+24	5.27E+24	8.98E+24	4.87E+24	3.87E+25	6.81E+25
2008	3.93E+24	4.07E+24	1.26E+24	1.06E+24	5.46E+24	9.06E+24	5.04E+24	4.11E+25	7.10E+25
2009	3.93E+24	4.07E+24	1.26E+24	1.06E+24	5.51E+24	8.83E+24	4.90E+24	4.03E+25	6.99E+25
2010	3.93E+24	4.07E+24	1.26E+24	1.06E+24	5.82E+24	9.03E+24	5.24E+24	4.54E+25	7.58E+25

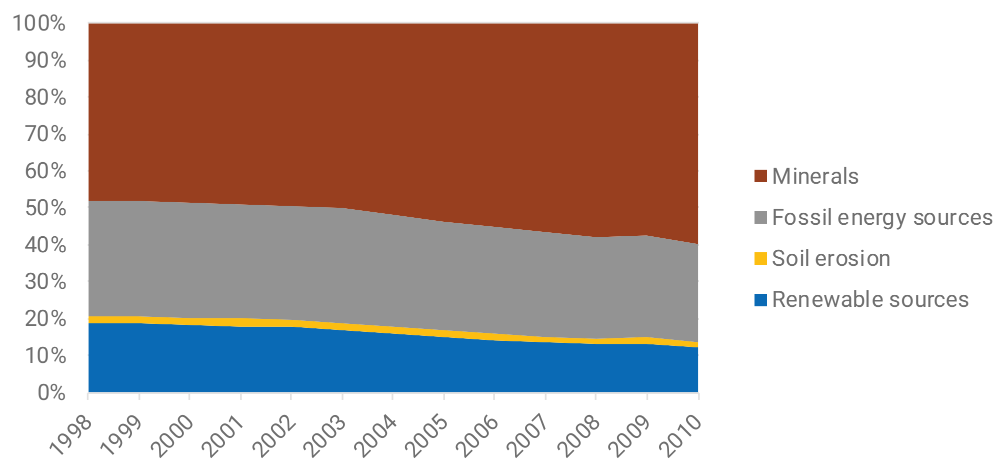
Source: This study.

3.3.2.11 **Services in imports** (Line #28 in Table 2-5)

The annual global emergy use (global U) or 'global emergy flows' was estimated for the period from 1998 to 2010. The 'global U' values were required in order to compute the UEV of "Services in imports" in the E4-emergy database for South Korea. Because the global emergy baseline (9.26E+24 sej/yr) is already given as the renewable emergy flow (D. E. Campbell, 2000), this study collected data for soil erosion, fossil fuel production (coal, oil, natural gas)), and minerals production. Table A-7 and Figure 3-1 show how each component of global emergy flows changes year over year.



a) Global emergy flows



b) Share of disaggregated emergy flows

Figure 3-1: Changing shares of global emergy components.
Source: This study.

Once the global emergy flows are estimated, the UEVs of ‘services in imports’ can be calculated by dividing the total global emergy flows by each year’s gross world product. The results are presented in Table 3-4.

Table 3-4: Annual change in UEV of ‘services in imports’

Year	Global emergy flows	Gross World Product	UEV of "Services in imports"
	sej/yr	current US$	sej/$
1998	4.99E+25	3.00E+13	1.66E+12
1999	4.98E+25	3.12E+13	1.60E+12
2000	5.13E+25	3.20E+13	1.60E+12
2001	5.20E+25	3.19E+13	1.63E+12
2002	5.27E+25	3.32E+13	1.59E+12
2003	5.48E+25	3.73E+13	1.47E+12
2004	5.86E+25	4.20E+13	1.40E+12
2005	6.19E+25	4.55E+13	1.36E+12
2006	6.54E+25	4.93E+13	1.33E+12
2007	6.81E+25	5.56E+13	1.23E+12
2008	7.10E+25	6.10E+13	1.16E+12
2009	6.99E+25	5.79E+13	1.21E+12
2010	7.58E+25	6.32E+13	1.20E+12

Source: This study, UNSD (2012).

3.3.2.12 **Services in exports** (Line #40 in Table 2-5)

UEVs of “services in exports” are determined by dividing each year’s total emergy use (“U”) by that year’s GDP. Then the emergy values of “services in exports” are calculated by multiplying each year’s exports in nominal US dollars by the UEVs.

3.3.2.13 Grouping of traded resources

"HSK" stands for "Harmonized System of Korea." It is specified according to the International Convention on the Harmonized Commodity Description and Coding System. The aggregation of traded commodities in the database followed Nam and Lee (2010).

3.3.2.14 Avoiding double counting in the renewable emergy inflows calculation

The total renewable emergy inflow is the emergy sum of the chemical potential of rain, wave energy, and the adjusted tidal energy. The sum of tidal emergy must be corrected to avoid double counting by removing the surf zone from the tidal input.

In South Korea, nine buoys have been recording hourly wave data all year long. As Table 3-5 shows, most buoys are located in deep waters. In addition, according to the KMA measurement data from the buoys, the mean wave period (T) in South Korea was approximately **5.609877 seconds** in 2012 (KMA, 2012b, 2013).

Table 3-5: Marine meteorological observation stations

Station (buoy)	Water depth (m)
Ulleungdo	2,200
Deokjeokdo	30
Chilbaldo	33
Geomundo	80
Geojedo	87
Donghae	1,518
Pohang	310
Marado	130
Oeyeondo	47

Source: KMA (2012b, 2013).

According to a manual for wave analysis from the World Meteorological Organization, wavelengths and wave celerities depend on water depths by the following two sets of equations. When T = wave period, λ = wavelength, c = wave celerity, and h = water depth,

(1) In deep water ($h > \lambda/4$),

$\lambda = 1.56\ T^2$

$c = 1.56\ T$

Because $T = 5.609877$ seconds,

$\lambda = 1.56 \times (5.609877)^2 = 49.09$ m, ($= \lambda_0$)

$c = 1.56 \times (5.609877) = 8.75$ m/s. ($= c_0$)

$\therefore \lambda/25 = 49.09/25 = 1.9636$ m

$\lambda/4 = 12.2725$ m

Then

c_0 = the deep-water wave speed,

λ_0 = the deep-water wavelength,

k_0 = the deep-water wavenumber = $2\pi/\lambda$ ($\approx 2 \times 3.14159/49.09 \approx 0.128$)

(2) If a wave is travelling in water with depth $\lambda/25 < h < \lambda/4$,

$c = c_0 \times \text{SQRT}(\tanh(k_0 h))$

$\lambda = \lambda_0 \times \text{SQRT}(\tanh(k_0 h))$

If the wave shoaling depth ***h* = 2 meters** is used,

(1.9636 m $< h <$ 12.2725 m)

$c \approx 8.75 \times \text{SQRT}(\tanh(0.128 \times 2)) \approx 4.38$ m/s,

$\lambda \approx 49.09 \times \text{SQRT}(\tanh(0.128 \times 2)) \approx 24.57$ m.

Then the water depth of interest can be found. Here, $\lambda/2$ = 12.29 meters. So the shallow water wave equation would apply in water at anything less than 12.29 meters.

By the way, the area of South Korea's continental shelf is 68,902 km^2 (MOF, 2013). And the area of surf zone (wave breaker zone) is 13,479.1 km^2, because the area of the ocean whose depths are less than 10 meters is 13,479.1 km^2. The water in the breaker zone (= surf zone) is slightly deeper than 10 meters ("anything less than 12.29 meters"), the area calculated here is the area of the sea that is less than 10 meters deep.

Table 3-6: Areas of territorial waters by depths

Depth	Total		Cumulative total	
	Area (km^2)	%	Area (km^2)	%
0 - 5 m	9,688.8	13.7	9,688.8	13.7
5 - 10 m	3,790.3	5.4	13,479.1	19.1
10 - 20 m	7,882.6	11.2	21,361.7	30.2
20 - 30 m	6,505.8	9.2	27,867.5	39.4
30 - 40 m	5,670.7	8.0	33,538.2	47.5
40 - 50 m	5,540.9	7.8	39,079.1	55.3
Deeper than 50 m	31,592.1	44.7	70,671.2	100.0
Total	70,671.2	100.0		

Source: Lee (2000).

Then the total renewable emergy inflows in South Korea can be calculated. The renewable emergy base in South Korea is the sum of the following three components: chemical potential energy of rain (land), wave energy, and tide energy (corrected for the area of wave breaking).

According to the data from MOF (2013) and Lee (2000), 68,902 km^2 = continental shelf area, and

13,479.1 km^2 = the area of the ocean whose depths are less than 10 meters.

Now, the amount of tidal emergy corrected for the area of wave breaking can be adjusted. Using the numbers from Table 3-7,

1.274E+22 + 9.441E+21 + 3.066E+22 × (1 - 13479.1/68902) ≈ 4.685E+22,

which means that South Korea received 4.685E+22 sej of renewable emergy in 2010.

Table 3-7: Total renewable emergy inflows in South Korea in 2010

No	Item	Raw energy inflow (J/yr)	Solar transformity (sej/J)	Transformity reference	Solar emergy (sej/yr)
1	Sun	5.83E+20	1	By definition	5.83E+20
2	Wind, kinetic energy	5.49E+17	1.47E+03	(Odum, 1996)	8.06E+20
3	**Rain, chemical (land)**	7.04E+17	1.81E+04	(D. E. Campbell & Ohrt, 2009)	**1.27E+22**
4	Rain, chemical (shelf)	2.04E+17	1.81E+04	(D. E. Campbell & Ohrt, 2009)	3.69E+21
5	Rain runoff, chemical	4.08E+17	1.81E+04	(D. E. Campbell & Ohrt, 2009)	7.39E+21
6	Rain runoff, geopotential	2.23E+17	2.72E+04	(Odum, 1996)	6.07E+21
7	**Waves**	3.15E+17	3.00E+04	(Odum, 1996)	**9.44E+21**
8	Earth cycle	1.89E+17	3.37E+04	(Odum, 1996)	6.38E+21
9	**Tide**	1.26E+18	2.43E+04	(D. E. Campbell, 2000)	**3.07E+22**
	Total Renewable Emergy Flow	Largest land flow + Waves + Tide (corrected for the area of wave breaking)			**4.68E+22**

Source: This study.

3.3.2.15 GDP figures used in the emergy evaluation

In the case of South Korea, the GDPs expressed in Korean currency ('won') are significantly different from the GDPs expressed in US dollars, because the exchange rates heavily affect them. The country's nominal GDP values in won are not changing so much as the nominal GDPs in US dollars even during international economic turmoil such as the 1997-1998 Asian financial crisis (Ba, 2013) or the 2008-2009 Great Recession (Havemann, 2013). For example, even if Korea's GDP in US dollars shrank due to the harsh devaluation of Korean won during the crises, its GDP in won grew or showed a lot less negative changes during the global financial crisis (Figure 3-2). In addition, there are concerns on currency speculation or effects of the quantitative easing by the United States on the real value of South Korea's economy.

However, as one of the goals of this study is to compare emergy accounting with conventional energy accounting, the true wealth accounting using emergy had better be compared with the conventional GDP accounting, too. Then what currency does conventional GDP accounting use? Although the South Korean government is publishing the country's GDP values both in won and in US dollars, South Korean people use only US dollars when they compute per capita GDP. In addition, all the receipts from exports and payments for imports are recorded in current US dollars. Therefore, it could be said that the *de facto* currency used in South Korea's GDP and trade accounting is US dollars. In addition, if this study uses US dollars in emergy evaluation, it is easier to compare GDP-related indices with emergy indicators.

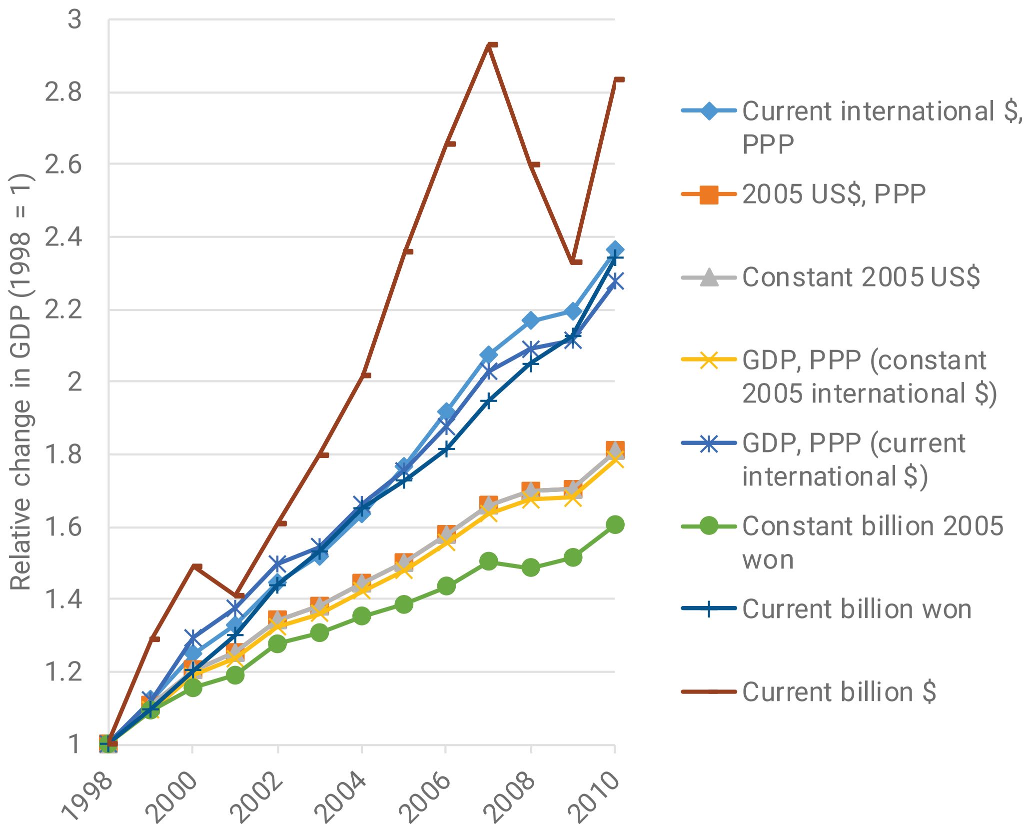


Figure 3-2: Relative changes in South Korea's GDPs expressed in different currency accounting methods.
Source: BOK (2013), OECD (2012), UNSD (2012), World Bank (2013).

3.4 Equity Data Collection

The equity data examined in this study are exclusively about residential energy consumption. The first information required to perform a household energy equity analysis is to determine the share of residential energy consumption in the total final energy consumption of the nation (Table 3-8). In addition, residential energy consumption should be disaggregated into different end-use energy types to be used in the emergy analysis (Figure 3-3). The results are summarized in the following table and figure.

Table 3-8: Final energy consumption in South Korea (1000 toe)

Year	Final energy consumption	Final energy consumption by sector (% share of each sector)									
		Industrial		Residential		Commercial		Transport		Public & etc.	
1998	**132,128**	76,039	(58%)	**17,407**	(13%)	10,011	(8%)	26,184	(20%)	2,487	(2%)
1999	**143,060**	79,858	(56%)	**20,276**	(14%)	11,653	(8%)	28,625	(20%)	2,648	(2%)
2000	**149,852**	83,912	(56%)	**21,401**	(14%)	10,969	(7%)	30,945	(21%)	2,625	(2%)
2001	**152,950**	85,158	(56%)	**21,673**	(14%)	11,220	(7%)	31,909	(21%)	2,989	(2%)
2002	**160,451**	89,197	(56%)	**22,508**	(14%)	11,791	(7%)	33,763	(21%)	3,191	(2%)
2003	**163,995**	90,805	(55%)	**22,591**	(14%)	12,374	(8%)	34,632	(21%)	3,593	(2%)
2004	**166,009**	92,992	(56%)	**22,788**	(14%)	12,019	(7%)	34,615	(21%)	3,595	(2%)
2005	**170,854**	94,366	(55%)	**22,544**	(13%)	14,317	(8%)	35,559	(21%)	4,068	(2%)
2006	**173,584**	97,235	(56%)	**21,435**	(12%)	14,551	(8%)	36,527	(21%)	3,836	(2%)
2007	**181,455**	104,327	(57%)	**21,067**	(12%)	14,849	(8%)	37,068	(20%)	4,143	(2%)
2008	**182,576**	106,458	(58%)	**21,132**	(12%)	15,093	(8%)	35,793	(20%)	4,099	(2%)
2009	**182,066**	106,119	(58%)	**20,540**	(11%)	15,182	(8%)	35,930	(20%)	4,295	(2%)
2010	**195,028**	116,351	(60%)	**21,724**	(11%)	15,532	(8%)	36,938	(19%)	4,483	(2%)
CAGR ('98-'10)	**3.3%**	**3.6%**		**1.9%**		**3.7%**		**2.9%**		**5.0%**	

Source: KEEI (2012b).

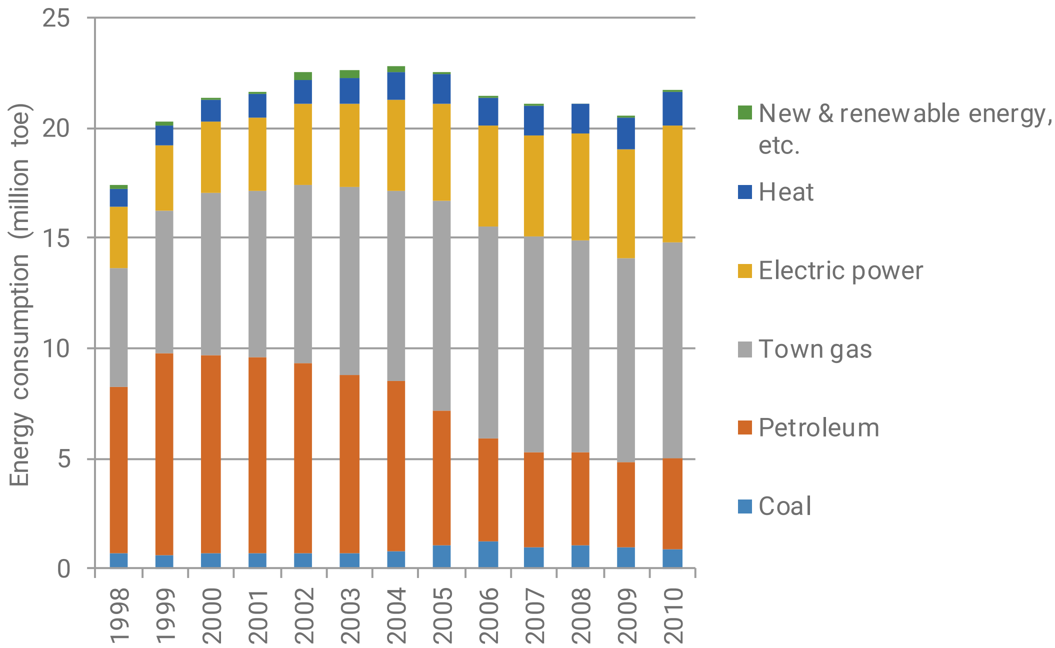


Figure 3-3: Final energy consumption by energy type in the residential sector. *Source:* KEEI (2012b).

Next, the data for the energy consumption per household by monthly income was obtained from the South Korean government's energy consumption surveys. Every third year, surveys were conducted on households' actual energy consumption in 1998, 2001, 2004, 2007, and 2010, respectively (KEEI, 2000, 2003, 2006, 2009, 2012a). This study compares differences between household emergy consumption at the five survey points taken at three-year intervals.

For example, as shown in the following table, the latest (2010) energy consumption survey of South Korea's residential sector reveals how households with different income levels consumed energy. These data are modified and integrated with the emergy database.

An important method to analyze energy consumption behaviors of households involves questions of how to classify households by their income. In this study, households are divided into quintiles. All households in the energy consumption surveys are rated by absolute incomes, not by income quintiles (i.e., aggregated by five 20% groups of total households from the lowest income to the highest income) or deciles (aggregated by ten 10% groups of total households from lowest income to highest income). Because the survey provides the shares of each absolute income group, income quintiles of households can be estimated.

Table 3-9: Energy consumption per household by monthly income (2010)

	Unit	Income distribution							
		Overall	under 1 million won	1 million–under 2 million won	2 million–under 3 million won	3 million–under 4 million won	4 million–under 5 million won	5 million–under 6 million won	6 million won and above
Total	Mcal	**12,701**	**10,046**	**11,854**	**13,252**	**14,215**	**14,932**	**14,563**	**15,868**
Briquette	Mcal	**230**	503	331	137	119	36	34	
Petroleum products	Mcal	**1,884**	2,658	2,255	1,885	1,369	982	749	259
Town gas	Mcal	**6,622**	4,236	5,952	7,188	7,843	8,302	7,632	8,654
Electricity	Mcal	**3,083**	2,295	2,858	3,195	3,543	3,670	3,588	4,042
Heat energy	Mcal	**883**	353	459	847	1,342	1,942	2,560	2,913
Energy cost	1000 won		966	1,166	1,342	1,475	1,540	1,484	1,670
Energy cost per 10,000 won income	"under 1 million" = 100		100	60	42	33	27	21	15

Source: KEEI (2012a).

3.5 Time Series E4-Emergy Database Development

As explained in a previous section, a time series database is essential for assessing the performance of policy options. To analyze the impacts of the South Korean government's energy and climate policy implementation since signing the Kyoto Protocol, all data are collected over the period from 1998 to 2010 from various individual sources. Applying the same principles to all the data collections and conversion processes in the emergy accounting over the period in which a certain policy has been implemented will yield insights about the direction of changes which the policy has caused.

3.6 Emergy-Equity Analysis of South Korea Over 13 Years

Emergy accounting can assess both aspects of equity: intergenerational equity and intragenerational equity. To do so, additional data processing is required.

To survey the emergy flows among different households according to monthly income, emergy-equity flow tables are developed for the years between 1998 and 2010 with a three year interval. In the tables, emergy flows from renewable and non-renewable resources to each income group are analyzed using both the conventional energy accounting and emergy accounting methods.

For the equity analysis, "emergy Gini coefficient" and "emergy Lorenz curves" are developed. The Gini coefficient is a good measure of inequity in income and resource distribution. Especially, the energy Gini coefficient indicates the distribution of energy access (Jacobson, Milman, & Kammen, 2005). Therefore, in this study, the Gini coefficients of the residential sector's emergy use are calculated from 1998-2010 in order to assess the changes in the energy equity among different income household groups. Time-series data for the task was collected from *Energy Consumption Surveys*

(KEEI, 2000, 2003, 2006, 2009, 2012a) that had been conducted every third year, covering the residential energy consumption in 1998, 2001, 2004, 2007, and 2010. A basic equation for emergy-Gini coefficients adopted from Jacobson et al. (2005) is:

$$G_{\text{emergy}} = 1 - \sum_{i=1}^{n} (Y_{i+1} + Y_i)(X_{i+1} - X_i)$$

Here, X_i is the share of an income group in total population and Y_i is the quantity of emergy used by the group in total emergy use with Y_i ordered from lowest to highest energy consumption. Energy-Gini coefficients (G_{energy}) and electricity Gini coefficients ($G_{\text{electricity}}$) were also calculated using the same equation, only by entering energy or electricity data in places of their emergy equivalents in the equation.

Emergy accounting can assess intergenerational equity and intragenerational equity, too. In fact, "the proportion of renewable to total energy in primary energy production" can be an indicator of intergenerational equity (Holden, Linnerud, & Banister, 2014).

Chapter 4

RESULTS AND DISCUSSION

4.1 E4-Emergy Evaluation of South Korea: An Overview

In the diagram (Figure 4-1), flows of materials, energy, and services are visually summarized with solid lines while numbers along the lines are the amount of emergy embedded in the flows. Flows of money as a payment for the emergy flows were expressed with dotted lines and values accompanying the lines are expressed in current (nominal) United States dollars.

While the System of National Accounts (SNA) (BOK, 2011), the Korea Energy Statistics Information System (KESIS) (KEEI, 2015), and the customs statistics (KCS, 2012b) track only money flows, energy flows, and the material trade flows respectively, the emergy accounts based on this diagram account for all the flows mentioned.

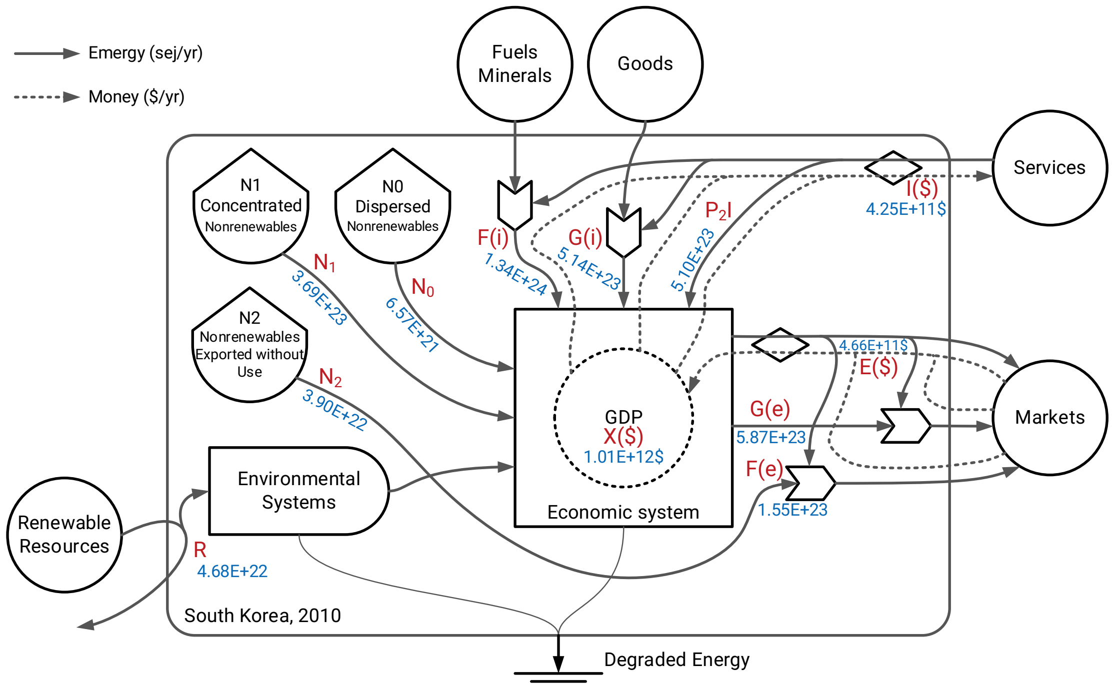


Figure 4-1: Aggregated diagram of South Korea's economy and emergy flows. *Note.* **R** = Renewable emergy flow; **N** = Total nonrenewable emergy flow (N0+N1+N2); **N0** = Dispersed nonrenewable production; **N1** = Concentrated nonrenewable use; **N2** = Nonrenewable flow - exported without full use; **F(i)** = Fuels, metals and minerals imports; **G(i)** = Goods and electricity imports; **I($)** = Money ($) for imports; **P2I** = Imported services; **F(e)** = Fuels, metals and minerals exports; **G(e)** = Goods and electricity exports; **E($)** = Money ($) for exports; **P1E** = Exported services; **X** = Gross Domestic Product (GDP); **P1** = National Emergy Money Ratio; **P2** = World Emergy Money Ratio; Annual flows or storages of each parameter are summarized in Table A-5 in the appendix. *Source:* This study.

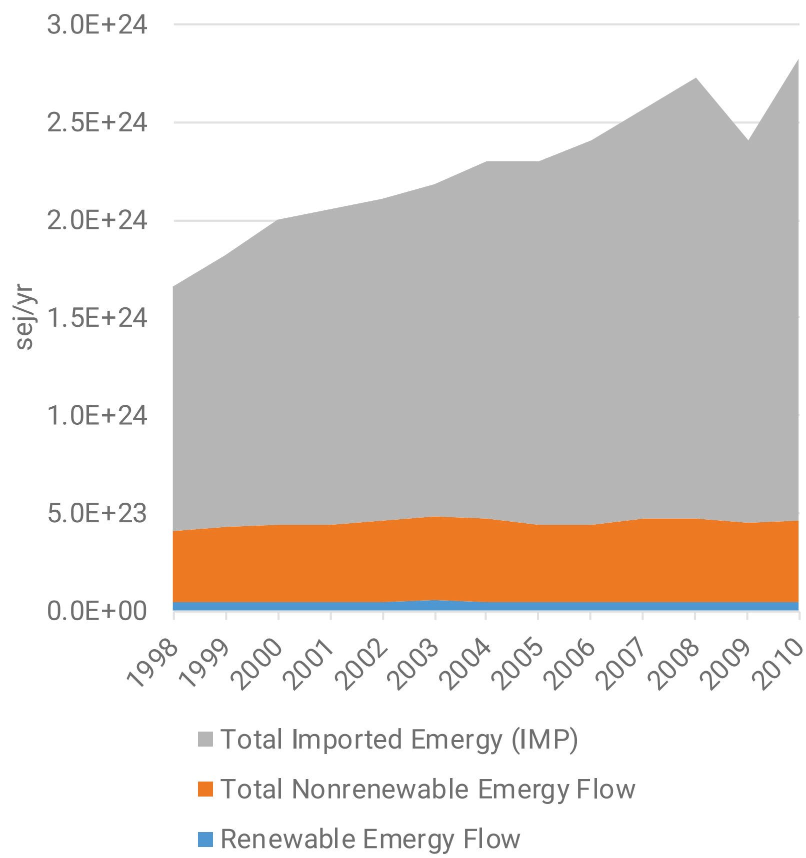


Figure 4-2: Sources of emergy inflows to South Korea.
Source: This study.

The Total Emergy Use (U) is a useful metric to show an overall picture of a country's resource appropriation. Traditional energy accounting methods cannot easily capture the meaning of total resource appropriation in a country. The main reason is that there is no common unit between different resources. For example, the sum of renewable energy supply (measured in energy units like megajoules) and the sum of the production of various minerals (measured in weights like metric tons) cannot be added together to make any kind of total domestic production of renewable and nonrenewable resources. In contrast, Figure 4-2 easily shows overall flows of resources in South Korea.

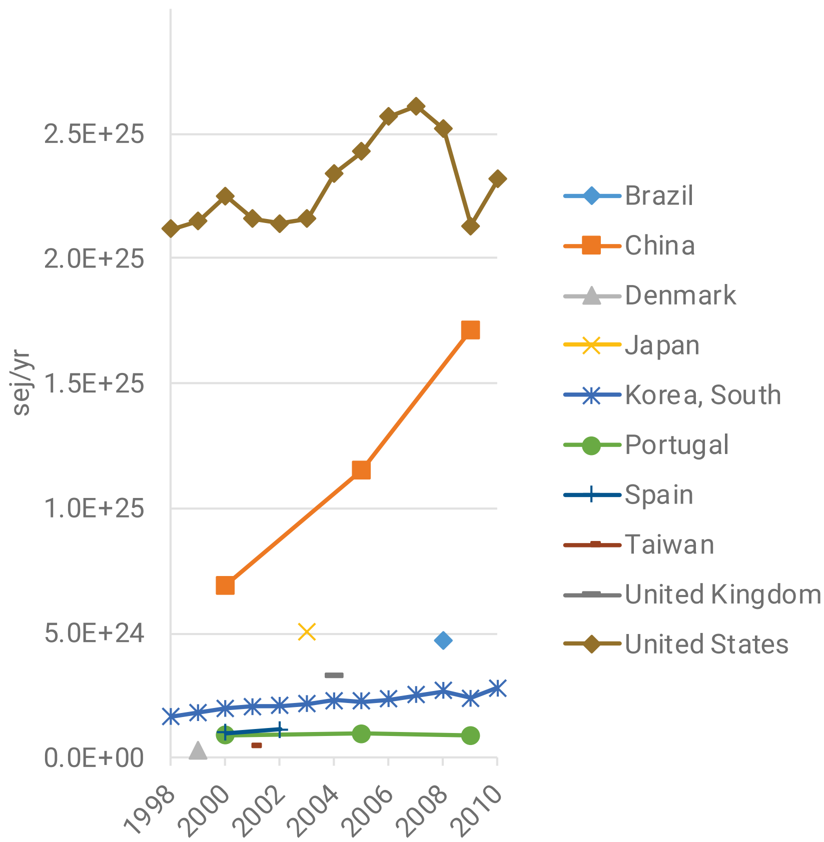


Figure 4-3: Total emergy used.
Source: This study (see Table A-11 in the appendix).

In terms of annual emergy use of the countries (Figure 4-3), South Korea's Total Emergy Use (U) has grown from 1.65E+24 sej in 1998 to 2.78E+24 sej in 2010 at an annual growth rate of 4.47% from 1998 to 2010. During the same period, the Total Emergy Use of the United State increased by 0.75% annually (D. E. Campbell, Lu, & Walker, 2014). According to Lou and Ulgiati (2013), China's Total Emergy Use increased by 10.63% each year during the recent ten years (2000-2009). In contrast, Portugal's Total Emergy Use declined by 0.38% annually from 2000 to 2009 (Oliveira et al., 2013).

Out of the Total Emergy Use, the renewable emergy flow constituted 3.0%, the non-renewable emergy 21.6%, and the imported emergy filled the remaining 76.2% in 1998. Over 1998-2010, the shares of domestic renewable and non-renewable emergy flows have declined while the share of imported emergy has increased. In 2010, the share of the renewable emergy flow was 1.7%. The share of the non-renewable emergy flow shrank to 14.9%. The imported emergy's share rose to 84.8%. This pattern is observed because the renewable emergy flows have declined at an annual rate of minus 0.43% during 1998-2010. Although the non-renewable emergy has grown by 1.28% annually, its share in the Total Emergy Use declined due to imported emergy's faster (5.41%) annual growth rate, which accounted for most of the growth of the Total Emergy Use over the 13 years examined.

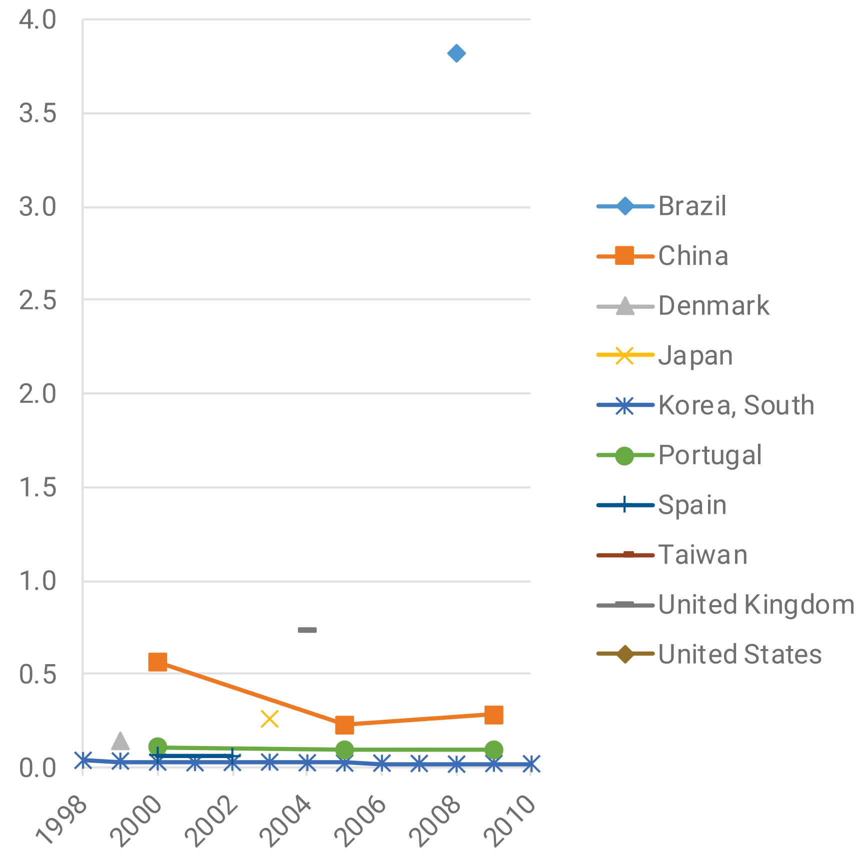


Figure 4-4: Emergy Sustainability Index.
Source: This study (see Table A-11 in the appendix).

The emergy sustainability index (ESI) is the ratio of the National Effect of Investment (NEI) to ELR; sustainability (ESI) increases with investment (NEI—to remain competitive) and decreases with environmental load (ELR) (Matthew J. Cohen, Brown, & Shepherd, 2006). This ratio was identified as the EYR for territorial systems by Brown and Ulgiati (1997); however, the ratio was criticized by Campbell and Garmestani (2012), who recognized that it actually indicates the response of the system to invested feedback, F, and not the yield to the next larger system, which is implied by the use of EYR. Thus NEI in this study is identical to the EYR of Brown and Ulgiati (1997), but it is interpreted differently. Campbell and Garmestani (2012) define the conventional EYR as Exp/Imp. The NEI is U/Imp. Campbell and Garmestani explain the NEI as the "effect of purchased emergy on system empower," while the conventional EYR is interpreted as "[e]mergy return to the larger system on its investments" (p. 78). This study adopted Campbell and Garmestani's version of ESI.

To transform the equation for NEI as NEI/ELR = [U/IMP] / [(IMP+N0+N1)/R] = [U×R] / [IMP × (IMP+N0+N1)], the emergy values of imports and nonrenewable resources become parts of the denominator. The emergy of total emergy use and domestic renewable resources become parts of the numerator. Figure 4-4 shows South Korea's extremely small share of renewable resources while imports and nonrenewable resources suppress the country's sustainability. This situation is made more evident when Brazil's ESI (3.819) is almost 200 times larger than that of South Korea (0.019) in 2008, thanks to the Amazonian country's vast domestic renewable resources.

4.2 E4-Emergy Evaluation of South Korea's Economy

4.2.1 Total energy/emergy use to GDP

It is true that the total primary energy supply (TPES) cannot simply be compared with the total emergy use (U). Still, the comparison of how the supplies of energy or emergy affect a country's economy (GDP) is a good indication of the specific information that emergy accounting can provide. D. E. Campbell, Lu, and Walker (2014) used emergy to explain performance of U.S. economy over time, which is a similar analysis to that of Laitner (2013) who analyzed the correlation between exergy and U.S. economy.

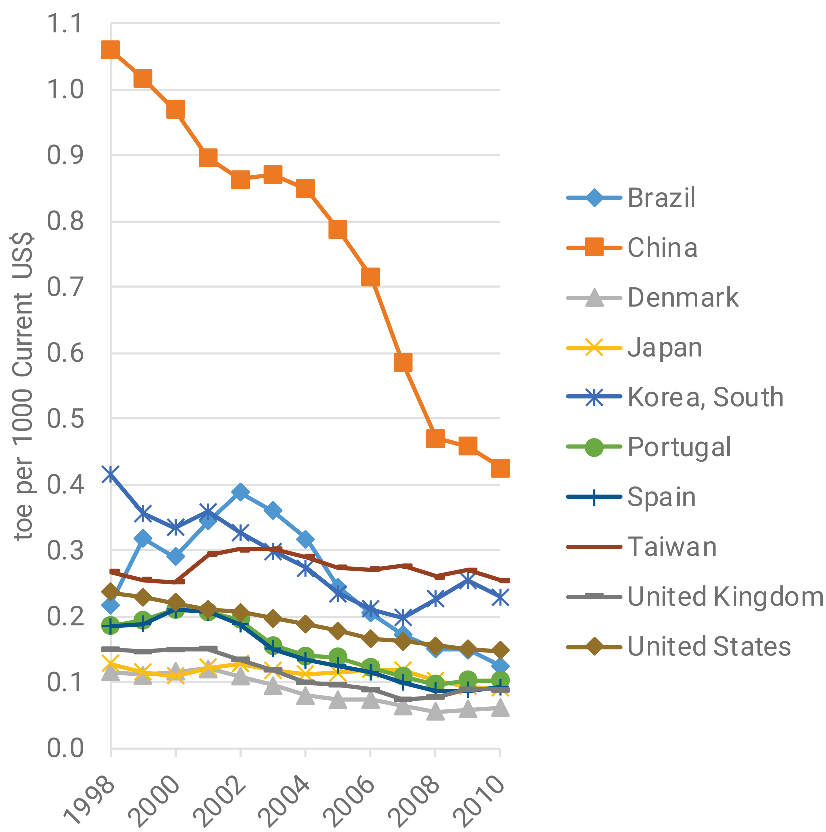
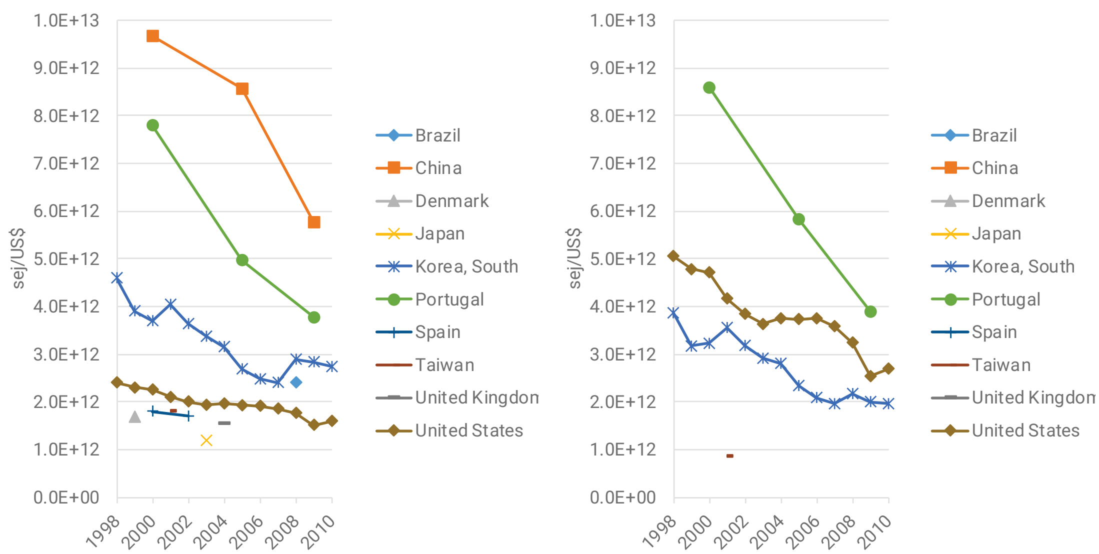


Figure 4-5: TPES to GDP in conventional energy accounts.
Source: BOE (2013), World Bank (2013).

According to Figure 4-5 and Figure 4-6, it seems that both TPES/GDP (energy intensity) and U/GDP (the Emergy to Money Ratio) are declining across countries as the countries' GDPs rose. However, South Korea and Portugal show a notable difference between the TPES/GDP and U/GDP. The two countries' rankings among the ten countries are higher in U/GDP than in TPES/GDP. Thus, they are using relatively more emergy to produce economic output than energy. In other words, they are not as efficient in their non-energy resource consumption as in energy consumption.



a) Emergy to Money Ratio (U / [Nominal GDP])

b) Emergy to Money Supply (M2) Ratio

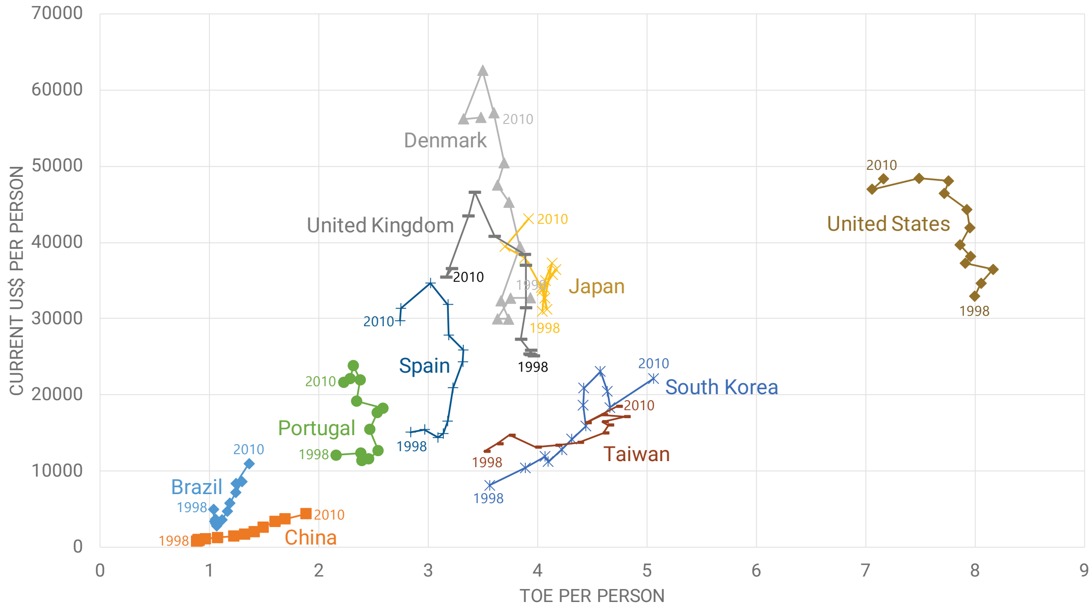
Figure 4-6: Total emergy use to GDP and money supply.
Source: This study (see Table A-11 in the appendix), FRED (2015a).

The Emergy to Money Ratio (EMR or U/GDP) seems heavily affected by money supply. The emergy to money supply (U/M2) ratios in South Korea, Portugal, and United States show similar trends as their EMRs (Figure 4-6). An interesting change between EMRs and U/M2 is South Korea’s better performance in emergy use per unit of money supply than the United States. Because South Korea is already third least efficient country in terms of U/GDP, United States' worse performance in U/M2 seems due to the country's increasing money supply rather than excessive emergy use. The time series data from the Federal Reserve Bank of St. Louis clearly shows the sustained decline in nominal GDP/M2 ratios at least since 1998 (FRED, 2015b).

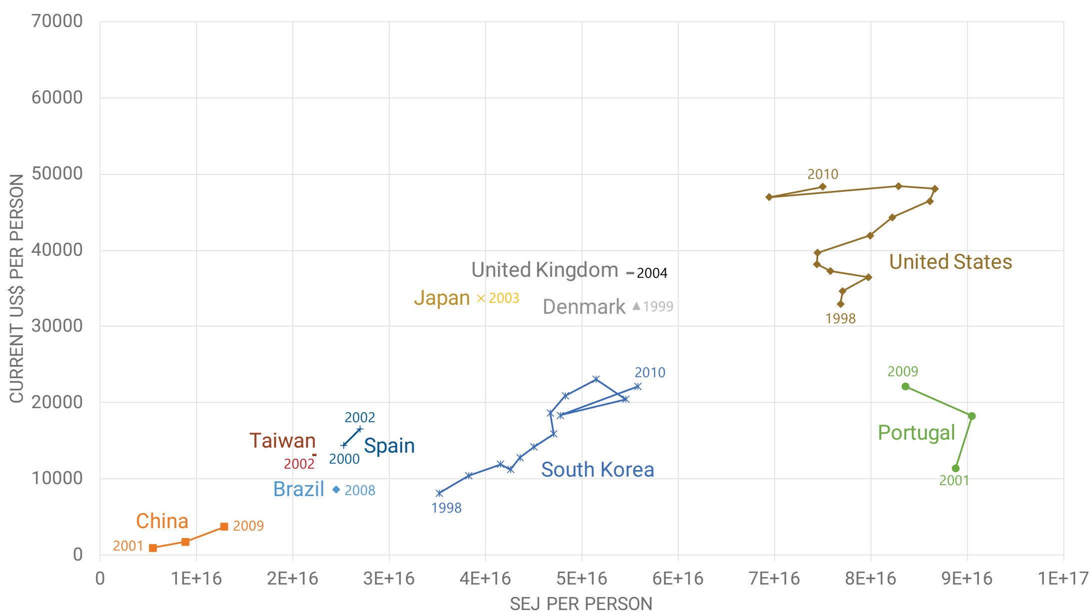
In addition, South Korea's U/M2 is a lot higher than that of Taiwan in 2001. Remembering the country's TPES/GDP ratios were comparable with those of Taiwan, South Korea is using more emergy for the same amount of money supplied.

In any case, South Korea's declining U/M2 reflects the widening gap between the flows of real wealth (total emergy used, in this case) and the money supply (Campbell et al., 2014). Kim and Yang (2012) found that M2/GDP rates have been over 150% of 1980 levels since the 1998 capital account liberalization, which had not happened at least since 1980. In 2009 and 2010, the rates were even higher, being over 200% of the 1980 levels. Therefore, to keep the value of the artificially supplied money from falling, the Korean government had to pursue GDP growth. This situation is a chronic problem of 'fractional reserve banking' systems and the financial derivatives propagated by these systems (Costanza et al., 2012).

South Korea, Taiwan, and China have shown increases in TPES per capita from 1998-2010 (Figure 4-7). South Korea and China show a consistent increase in the total emergy use per capita, too. But, in the case of South Korea, there is an important difference between the two. While the country's TPES per capita increased 1.4 times from 1998 to 2010, the total emergy use per capita increased 1.6 times. Although the growth of South Korea's energy consumption is already next only to that of China, the growth of emergy use is even more unrestricted.



a) TPES per capita vs GDP per capita

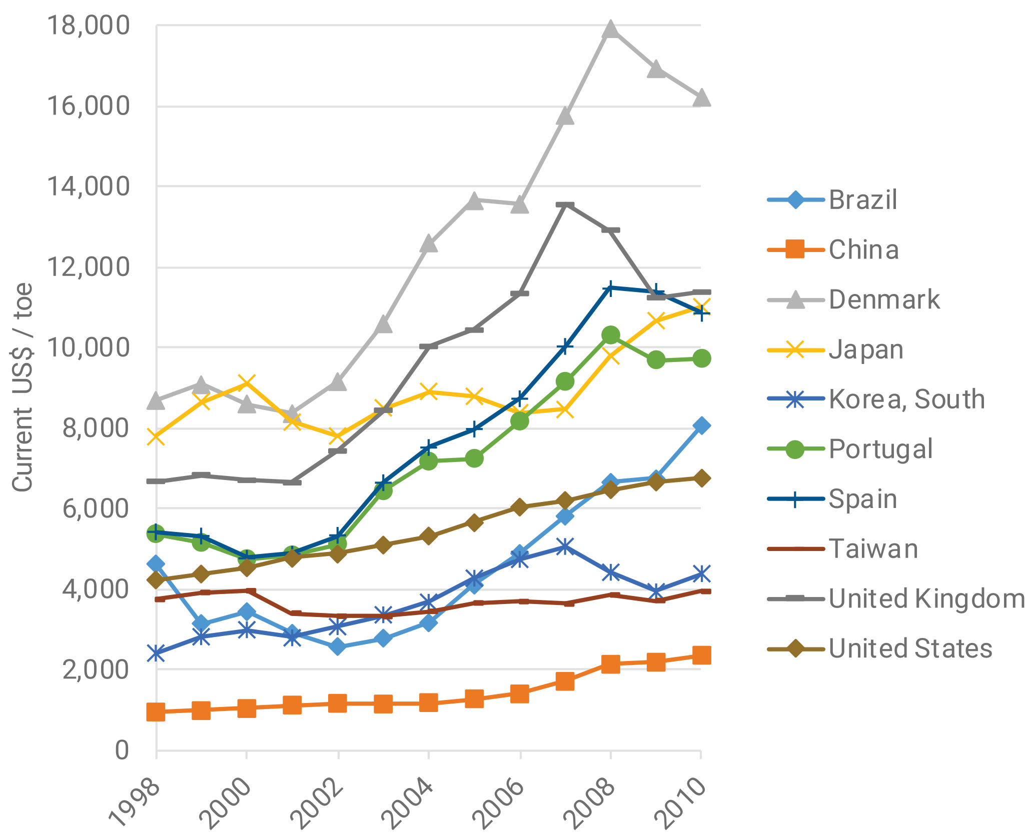


b) Total emergy use per capita vs GDP per capita

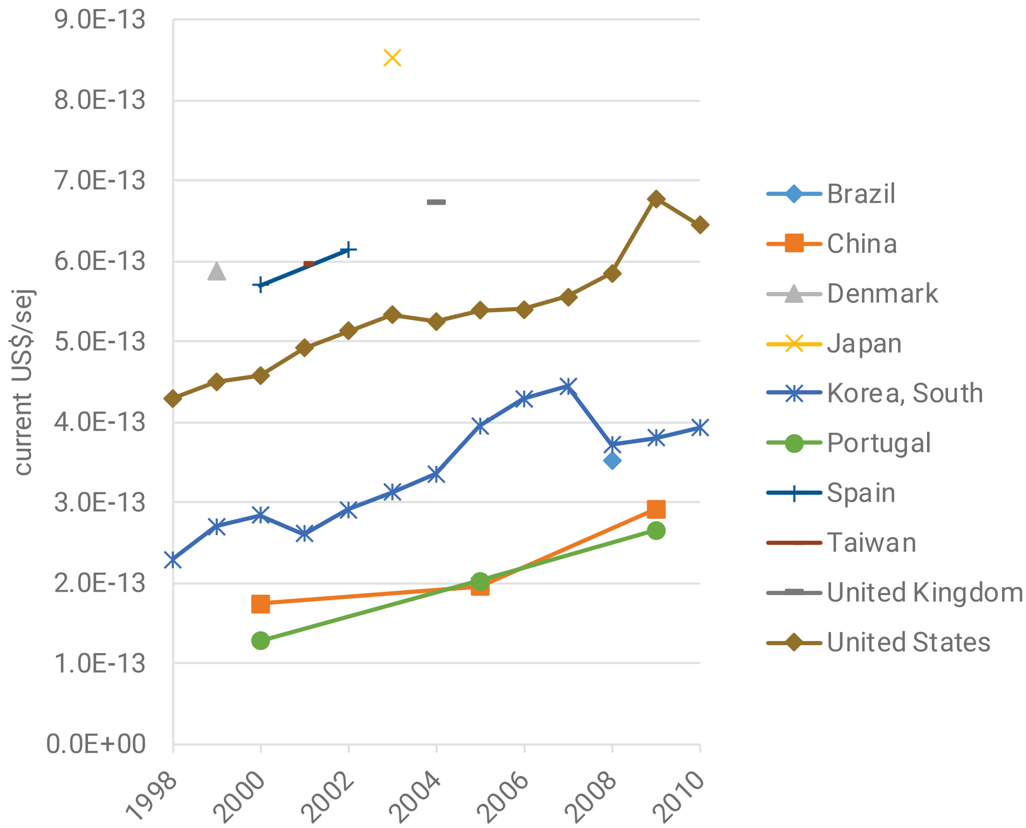
Figure 4-7: 'Per capita energy/emergy use' compared to 'GDP per capita.' *Source:* This study (see Table A-11 in the appendix), BOE (2013), World Bank (2013).

4.2.2 Economic efficiency of energy/emergy

The GDP/TPES ratio is the inverse of the energy intensity. The GDP/U ratio is the inverse of the emergy to money ratio. Although these inverse ratios do not offer entirely new information, they let people see the problems with different perspectives. Especially, the GDP/U ratio clearly shows that Japan is by far the most productive in converting its total emergy use into economic output. South Korea's economic efficiency of emergy use is of course relatively poor, being similar with that of Brazil (Figure 4-8).



a) [Nominal GDP] / TPES

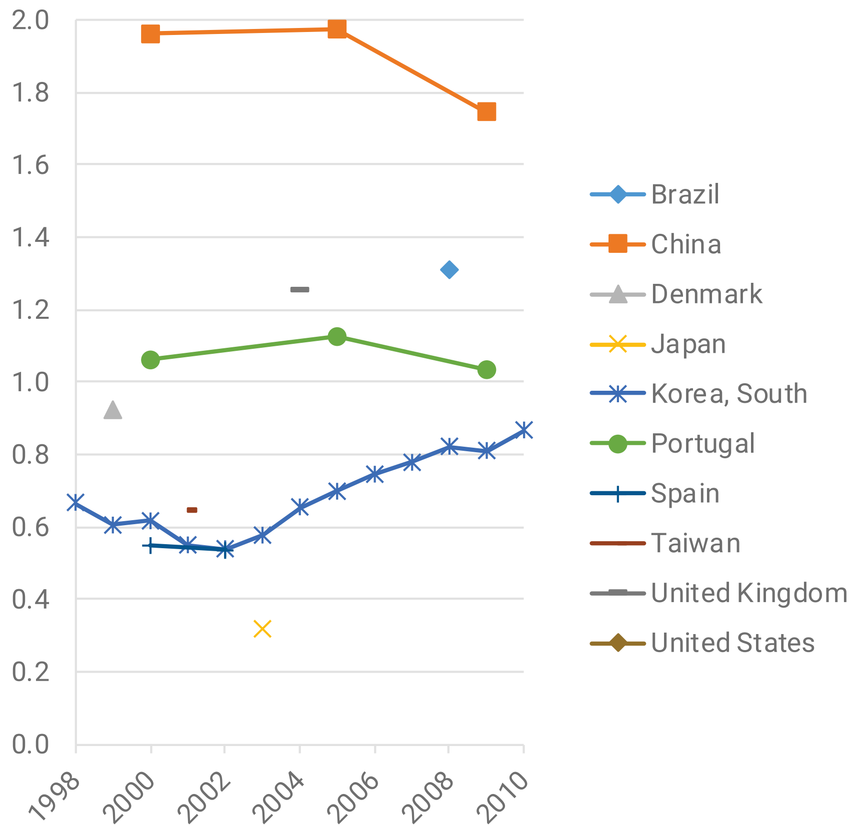


b) [Nominal GDP] / [Total Emergy Use]

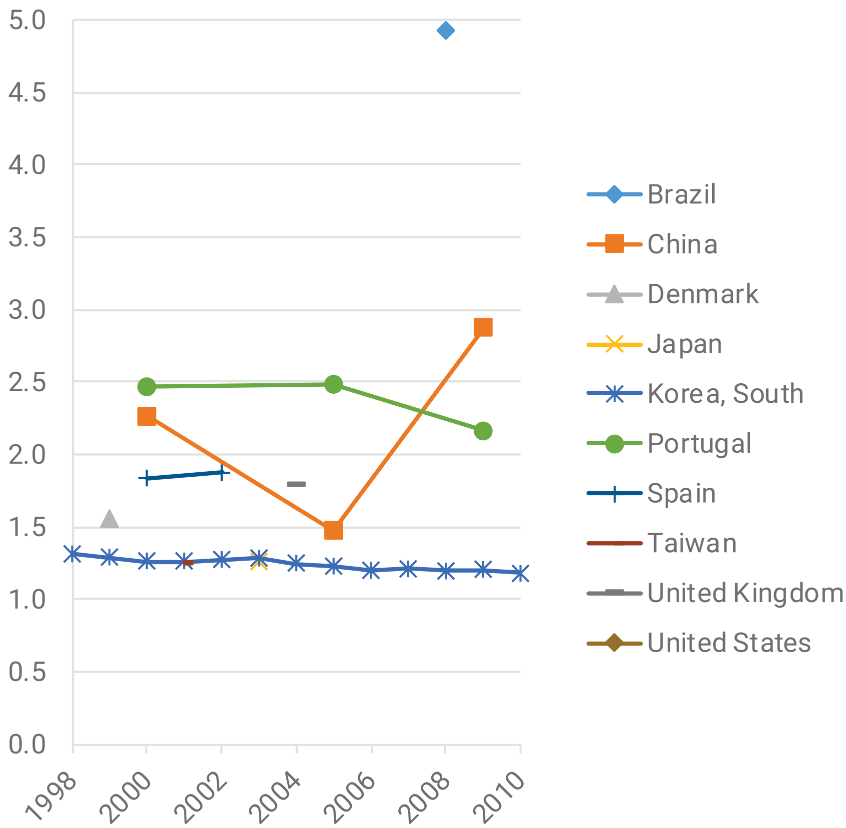
Figure 4-8: GDP per unit of energy/emergy use.
Source: This study (see Table A-11 in the appendix), BOE (2013), World Bank (2013).

4.2.3 Imports and exports

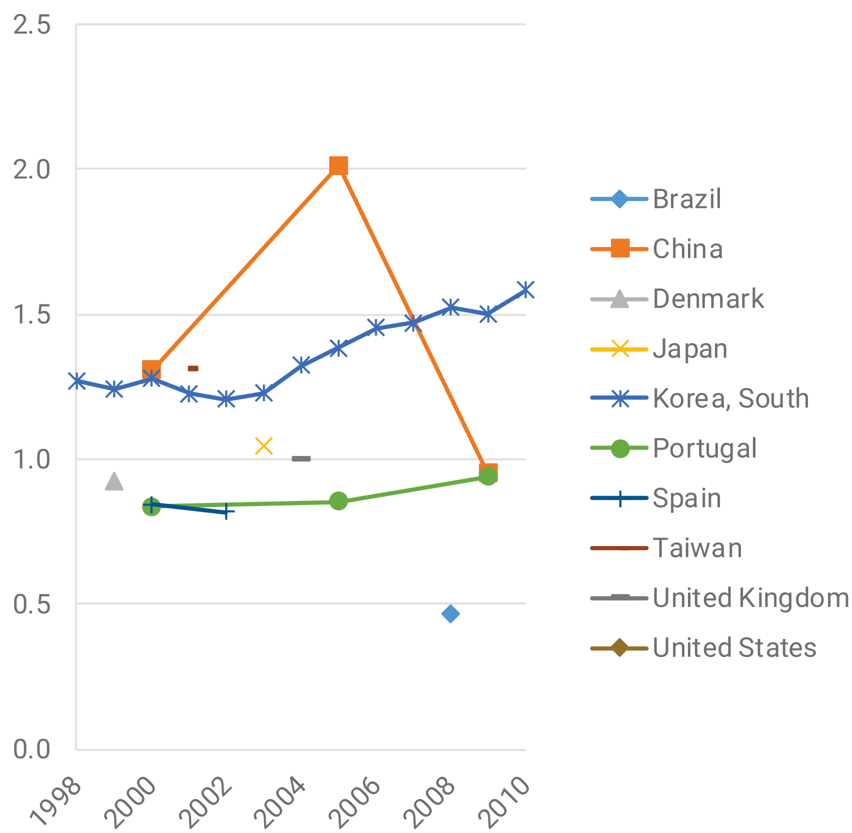
In terms of trade, there is not a good indicator or index in energy accounting that is comparable with emergy indicators or indices. So, this section focuses on emergy accounting.



a) National Emergy Yield Ratio (EXP/IMP)



b) National Effect of Investment (U/IMP)



c) Influence of traded emergy ([IMP+EXP] / [U])

Figure 4-9: Emergy influence on open economy.
Source: This study (see Table A-11 in the appendix).

The national Emergy Yield Ratio (i.e., total emergy exports divided by total emergy imports) gives a rare insight into South Korea's economic sustainability. Although the country is regarded as export-driven, its national EYR is the second or third lowest among the ten countries examined. Pane 'a' of Figure 4-9 demonstrates that only Japan and Spain have lower ratios than South Korea. A national EYR that is lower than 1 (one) means that the emergy exports are smaller than the emergy imports.

Although South Korea and Japan are well-known countries with trade surpluses, their emergy trade ended up negative.

This result indicates that South Korea consumes most of its imported emergy domestically. Although the country depends on commodity exports economically, the real balance of emergy trades shows that South Korea is, in a sense, a "black hole" for emergy. Of course, the same explanation could be applied to Japan, which has a lower national EYR.

This finding is partially supported by another emergy indicator. "The emergy yield ratio (EYR) is employed as a measure of the ability of a primary energy source to supply energy to an economy. In many ways it is equivalent to the energy return on energy invested (EROI)", "but differs in that the EYR has all flows in solar joules, whereas EROI is in available energy with some correction for upstream embodied energy uses." (Tilley, 2015) However, the EYR for territorial systems was recently renamed the 'Local Effect of Investment' or LEI (D. E. Campbell & Garmestani, 2012). In this study, however, LEI is named the 'National Effect of Investment' or NEI in order to emphasize that the evaluation is conducted on the entire country. Just as the conventional EYR, NEI represents U/F or in this case U/IMP.

Comparison of the National Effect of Investment, the ratio of the total emergy use to the emergy imports (U/IMP), shows that South Korea is the most vulnerable country in terms of the effect of the purchased emergy on national emergy use.

In this regard, South Korea should take note of China, another export-driven country. If the influence of trade ([emergy imports + emergy exports]/U) is examined, it becomes clear that total emergy use in both South Korea and China are heavily influenced by the sum of traded imports and exports, being greater than the countries' total emergy use.

However, China's national EYR is the largest of all ten countries and China's emergy exports are almost twice its emergy imports. In contrast, South Korea seems to be consuming a large portion of imported emergy within the country rather than re-exporting after transforming the resources.

4.2.4 Imports to domestic resource

Of course, energy accounting offers a few indices for the relationship between imports and domestic energy resources. However, those indices do not have particular 'economic' implications. Instead, two emergy indices offer some insights into the economic sustainability of South Korea.

The Emergy Investment Ratio is the ratio of emergy imports to domestic emergy resources. The Ratio of Purchased Emergy to Free Emergy is slightly different from EIR. It is the ratio of purchased emergy to free emergy resources (renewable emergy + emergy from topsoil loss).

The difference is easily explained by the following equations.

Emergy Investment Ratio = IMP / (R+N0+N1)

Ratio of purchased to free = [U - (R+N0)] / (R+N0) = (N1+IMP) / (R+N0)

Because,

Emergy use that is free = R+N0

Purchased emergy = U - (R+N0)

Total Emergy Used (U) = R+N0+N1+IMP

Where,

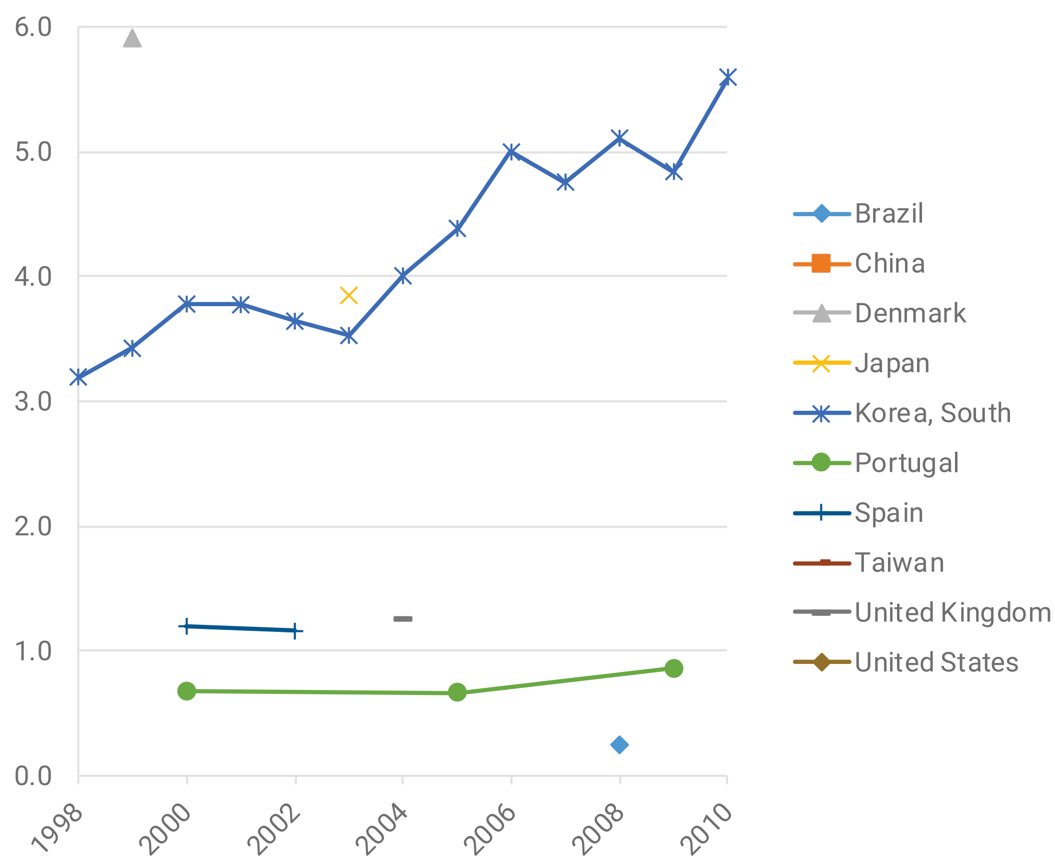
N = Total Nonrenewable Emergy Flow

N0 = Dispersed Nonrenewable Production ("renewable emergy used in a nonrenewable manner")

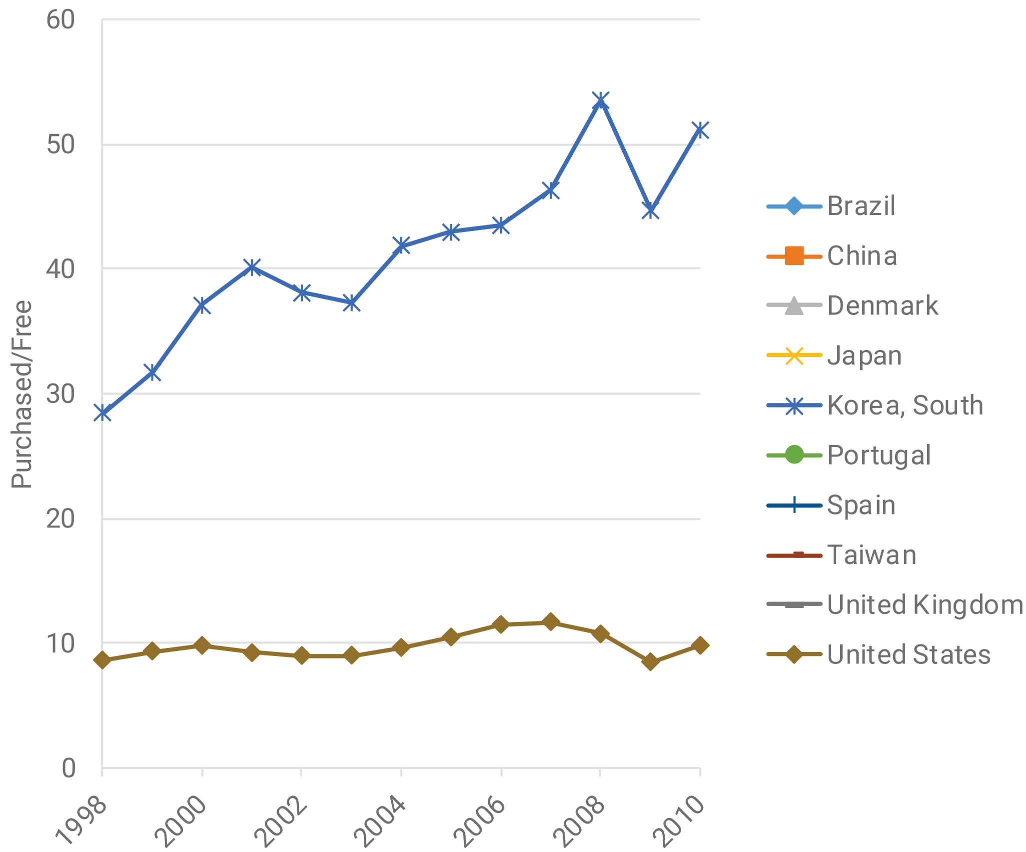
N1 = Concentrated Nonrenewable Use

N2 = Nonrenewable Flow (fuels/minerals/metals exported without full use)

N1+N2 = Concentrated Nonrenewable Production (fuels/minerals/metals production)



a) Emergy Investment Ratio (IMP / [R+N0+N1])



b) Ratio of purchased emergy to free emergy ([U-(R+N0)] / [R+N0] = [N1+IMP] / [R+N0])

Figure 4-10: Impacts of imported emergy.
Source: This study (see Table A-11 in the appendix).

South Korea's EIR is higher than those of four countries in the group (Pane 'a' of Figure 4-10). Although the country's EIR was smaller than that of Denmark in 1999 and that of Japan in 2003, it kept increasing. In 2004, Korea's EIR level surpassed Japan's. By 2010, South Korea's EIR (5.598) was almost as high as that of Denmark (5.910). Because the imported emergy's influence has been increasing in the country, less and less domestic resources have become available.

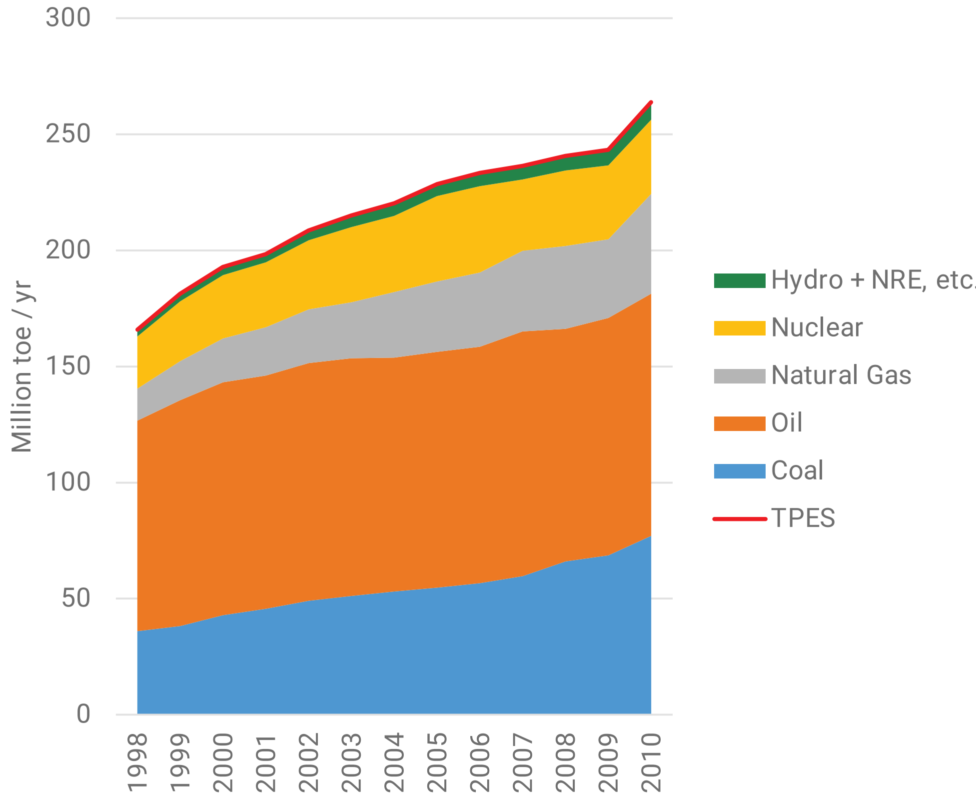
A similar index, the ratio of purchased emergy to free emergy, gives a good time-series comparison between South Korea and United States (Figure 4-10). United States' ratio has been stable around 10 over the study period. South Korea's ratio started below 30, but kept increasing, and ended up at over 50 in 2010. The availability of South Korea's freely endowed resources are becoming more scarce compared to the resources that are bought with money.

If there is no or little domestic or free indigenous emergy resources, South Korea's future reserve for additional economic investment will be eventually depleted. If unchecked, the unusually fast increase rates of South Korea's EIR and the purchased to free emergy ratio might soon threaten the country's economy.

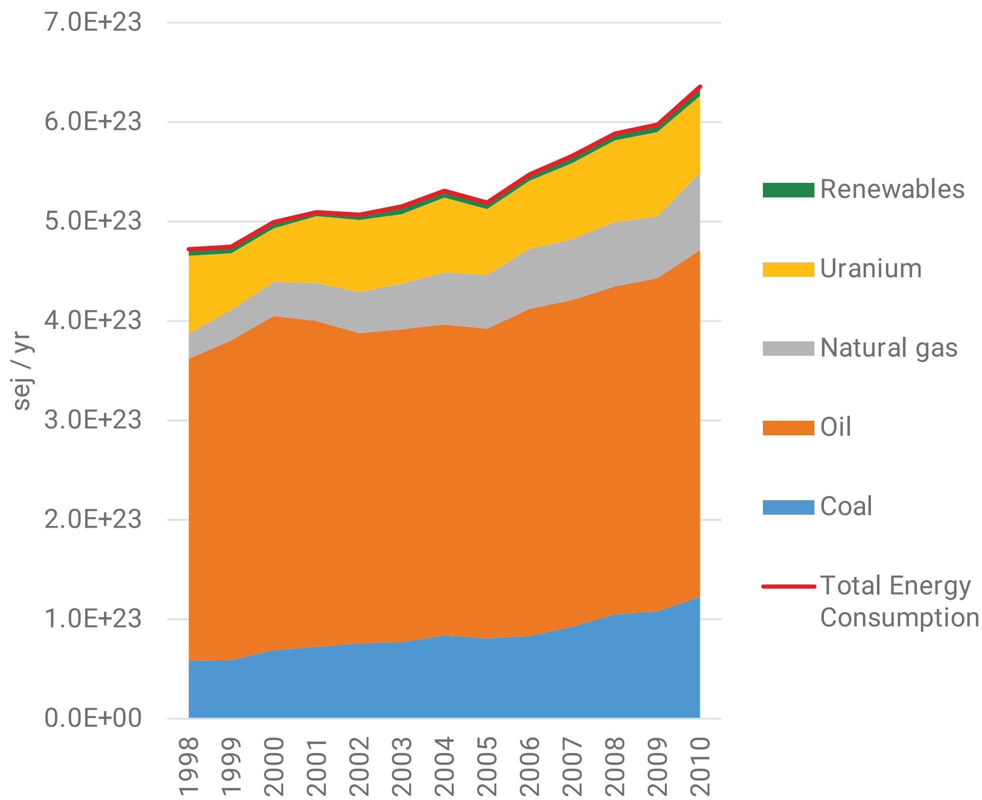
4.3 E4-Emergy Evaluation of South Korea's Energy

4.3.1 National energy supply

Emergy evaluation is different from conventional energy accounting in that it counts donor values rather than receiver- or market-values (Grönlund, Fröling, & Carlman, 2015). By contrast, in the conventional energy bookkeeping, neither non-energy environmental flows nor human labor and services are adequately accounted for. This omission leads to overestimation of direct fuel, heat or electricity inputs. On the other hand, the exergy that has been consumed to produce non-energy goods and machinery is inevitably underestimated (Brown & Ulgiati, 2004, 2007).



a) Primary energy supply by source



b) Emergy in energy consumption by source

Figure 4-11: South Korea's energy consumption by source.
Source: This study, KEEI (2012b).

The energy accounting shows a familiar picture of South Korea's primary energy supply over time (Pane 'a' of Figure 4-11). Oil accounts for most of the country's energy supply, coal is the second largest energy source, natural gas is the third, and nuclear energy is the fourth. The compound annual growth rate of TPES is 3.94 % from 1998 to 2010.

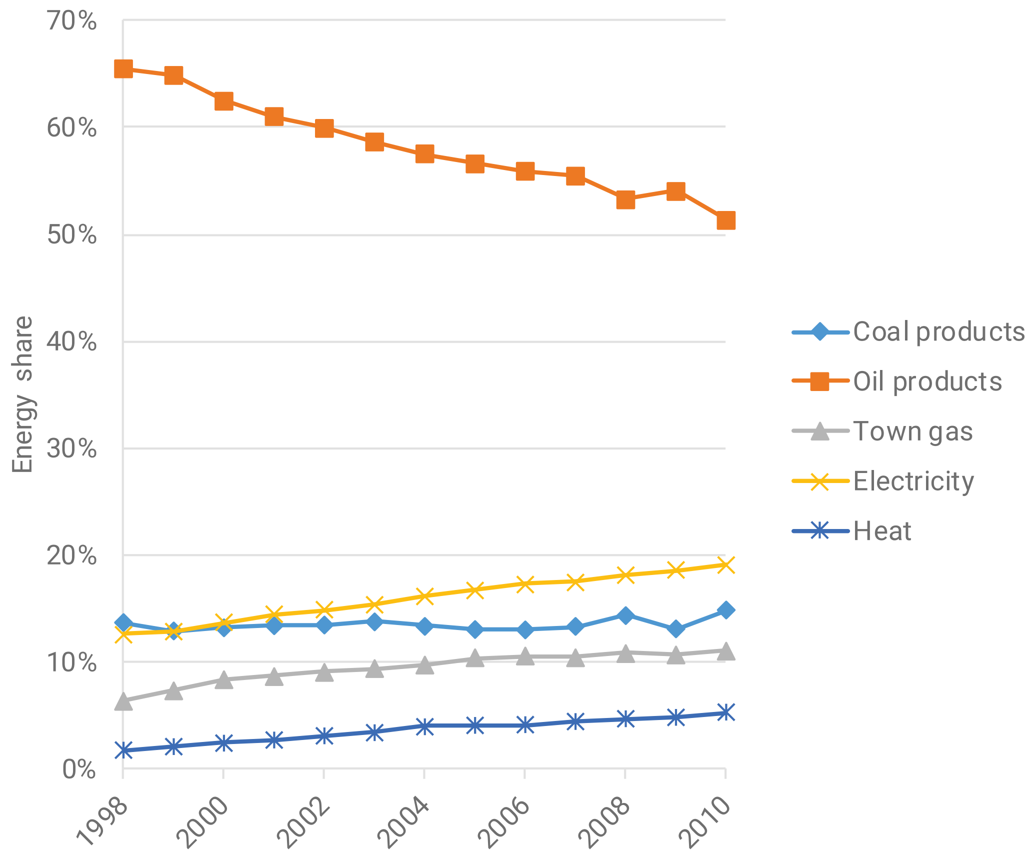
In comparison, the emergy accounting of the country's energy supply exhibits different shares of energy sources (Pane 'b' of Figure 4-11). Oil is now more than half of South Korea's energy supply in emergy terms. Coal, while still number two, supplied a relatively smaller share among energy sources. Natural gas's share is the fourth largest except in 2010 and uranium was the number three supplier of energy until the year 2010 when the import of uranium decreased. The already small share of renewable energy sources shrank in the emergy accounting over the time examined. The compound average annual growth of total energy consumption in emergy terms is 2.51 %, which is smaller than that of TPES in conventional energy accounting.

As explained above, the relative shares of each energy source can change according to the Unit Emergy Values (UEVs) of those sources. However, the biggest difference between the two different accounting methods is found in how nuclear energy is counted. The difference between the CAGRs of the two accounting results is mainly due to the freeze in uranium emergy supply (CAGR = -0.2 %), whereas nuclear energy increased 3.0% annually. In the energy accounting, as pointed out in a previous section, energy accounting only counts the nuclear electricity as the sum of nuclear energy. In contrast, the emergy accounting tallies the energy in the imported uranium. So when the nuclear fuels were imported doesn't matter in the energy accounting. As a result, it is easier for the emergy accounting methods to track the flows of nuclear energy.

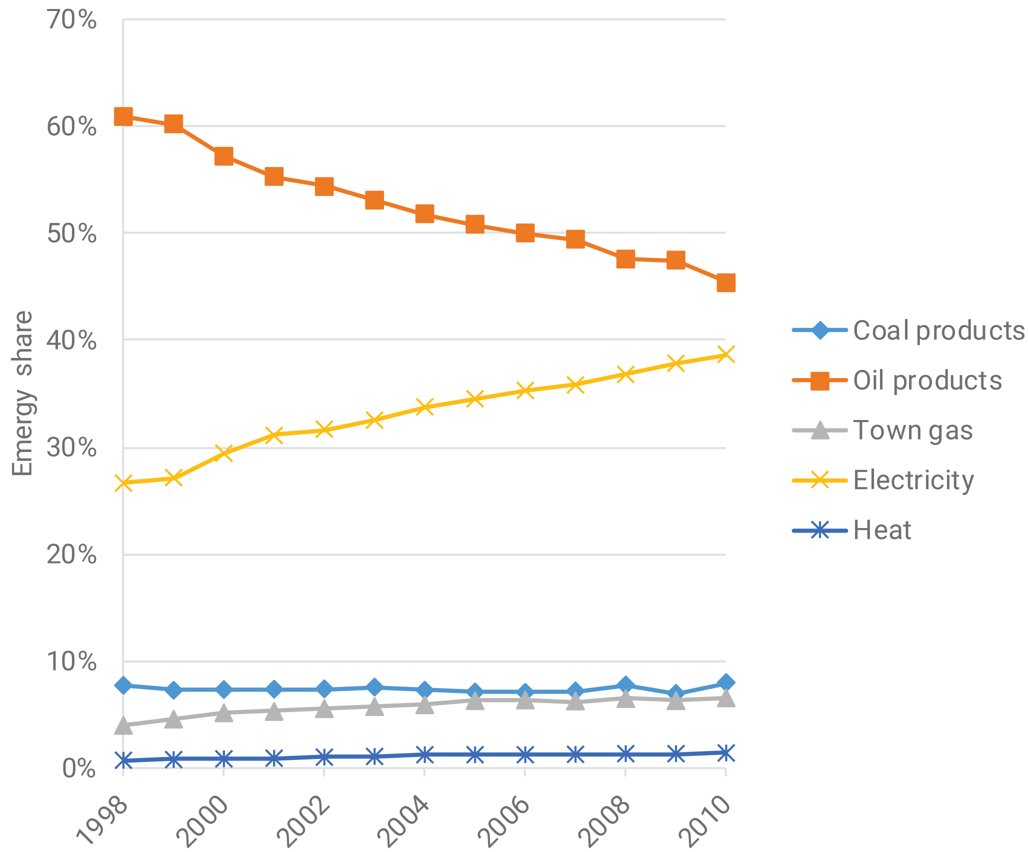
Why is the share of oil so large in the emergy accounting? Of course, the transformity of crude oil, 54200 sej/J, is larger than that of natural gas or methane, 43500 sej/J. It is larger than coal's transformity 39200 sej/J, too. This means that oil requires the most emergy to produce among the three fossil resources. Two reasons can be suggested. While 85% of the weight of oil is organic carbon, only 75% of natural gas's weight is made of the same matter. In addition, the enthalpy of natural gas (51300 J/g) is greater than that of oil (41900 J/g). The two aspects make the transformity of oil greater than that of natural gas (Bastianoni et al., 2005).

4.3.2 Final energy consumption

In the final energy consumption graphs (Figure 4-12), the change in the share of electricity within each accounting and between the two accounting methods is remarkable. First, electricity's share among the energy end-use kept increasing in both graphs. The increase came at the expense of oil's share. Secondly, the share of electricity is very different between the two accounting methods. In the energy accounting, the electricity supplied is less than 20% of the total final energy in 2010. In the same year, the emergy accounting found almost 40% of the emergy delivered in the forms of final energy was electricity.



a) Energy shares of final energy consumption



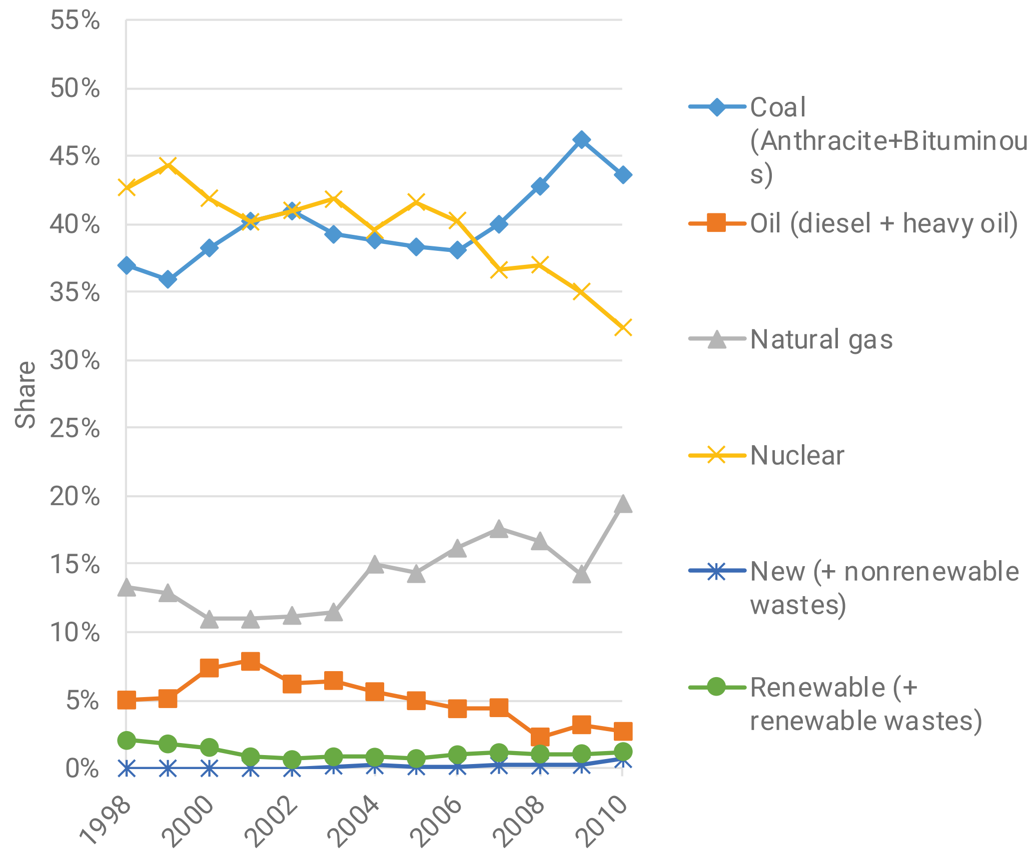
b) Emergy shares of final energy consumption

Figure 4-12: Shares of energy end-use forms.
Source: This study, KEEI (2012b).

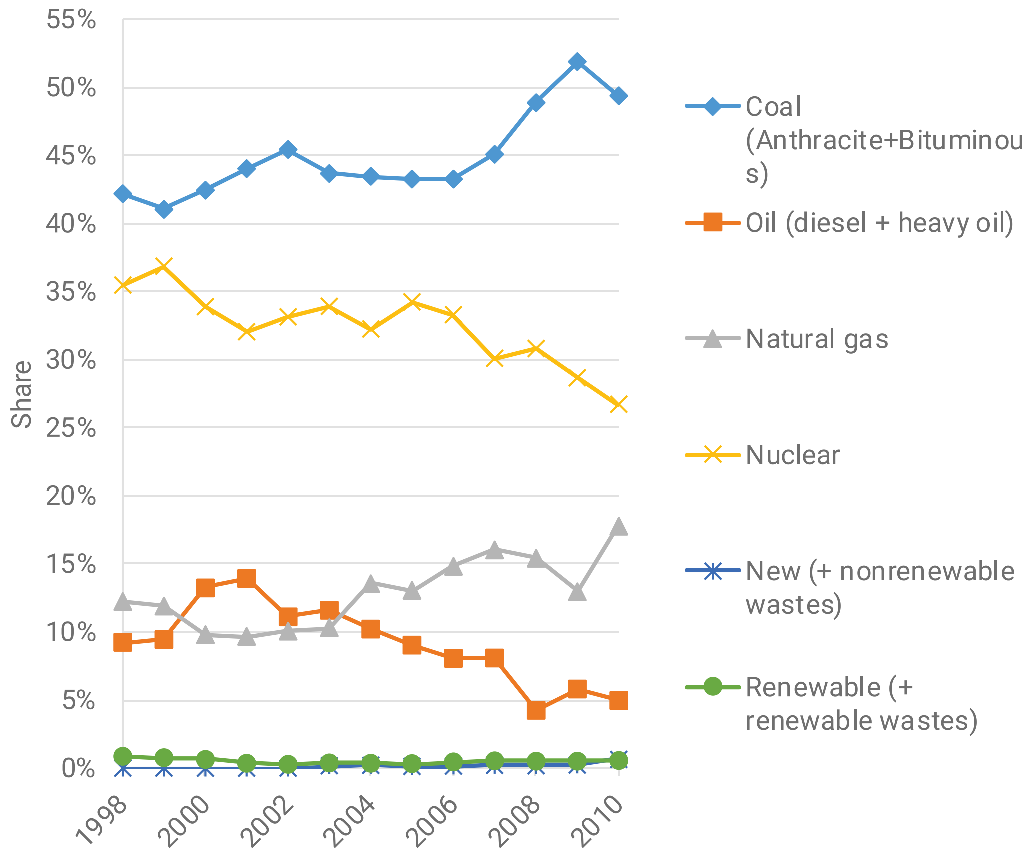
In the conventional energy accounting, the unit price of electricity was relatively cheaper than other final energy forms. The emergy accounting gives more information. Electricity's transformity (about 147400 sej/J) is 2.3–3.8 times higher than those of coal products (39200 sej/J), oil products (64700 sej/J), and city gas (43500 sej/J). The relatively higher transformity of electricity in South Korea further helped the rise of electricity's share of total use. A higher transformity of electricity means that more environmental resources were collected and concentrated in the production of this form of energy.

4.3.3 Energy sources in electricity generation

This comparison also shows the differences in the shares of the energy sources contributing to electricity generation (Figure 4-13). In both accounting methods, the shares of coal and natural gas have been increasing from 1998 to 2010. Shares of nuclear- and oil-generated electricity have declined over the same period. However, the relative shares of electric power sources were very different between the two accounting methods. Above all, coal's share in emergy terms is more than 49% in 2010, while its share in energy terms is about 44% in that year. Oil power's share in emergy accounting is 2-6% greater than accounted by the conventional energy statistics. In comparison, the emergy share of nuclear electricity is 6-8% smaller than its share in the conventional energy accounting. In addition, the already small renewable power's share by the energy accounting becomes even smaller in the emergy accounting (about 55% smaller on average throughout the period).



a) Energy share of each technology in total electricity sales



b) Emergy share of each technology in total electricity sales

Figure 4-13: Energy sources in electricity generation.
Note.
1) Renewable (+ renewable wastes) = solar PVs, biogas, landfill gas, wind, hydro, ocean (tidal)
2) New (+ nonrenewable wastes) = product gas, waste-burnup
Source: This study, KPX (2015).

This finding means coal power's environmental impacts are greater in the E4-Emergy evaluation than conventional energy accounting. The same reasoning applies to the oil-generated electricity. On the contrary, renewable power has more room to be developed. They demand a lot less natural resources to produce the same electricity, from the emergy accounting perspective.

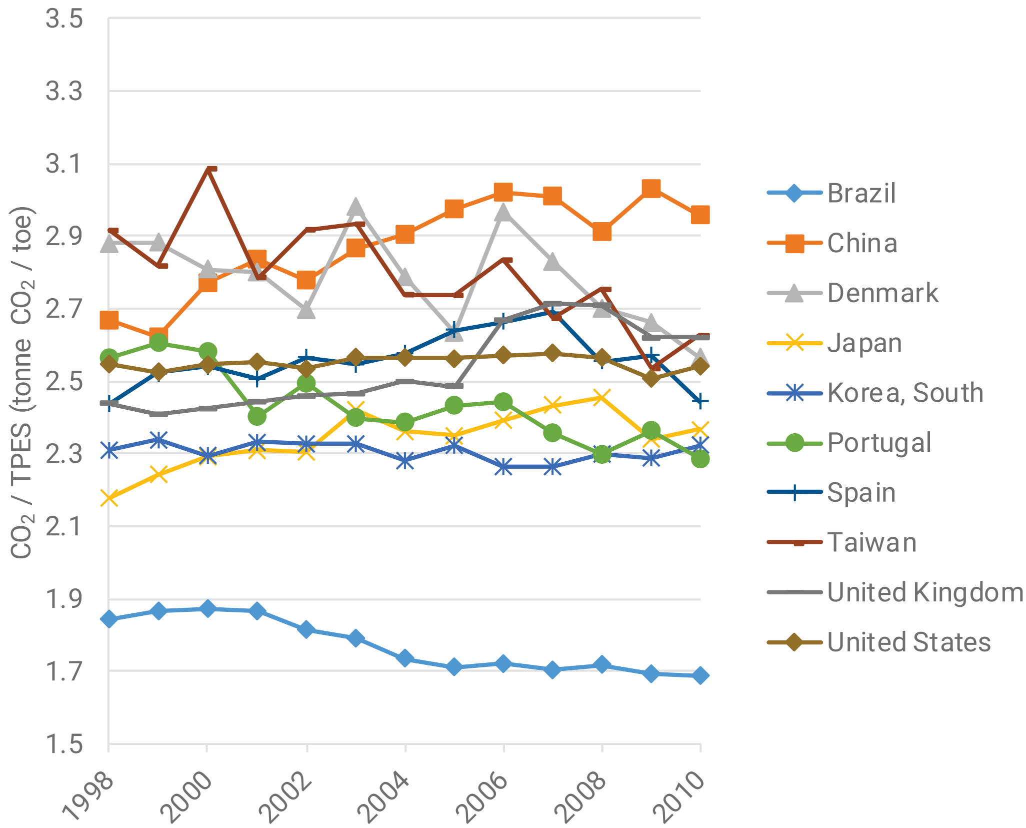
4.4 E4-Emergy Evaluation of South Korea's Environment

International organizations such as the United Nations and the World Bank admit that the current mineral and energy resource accounts are separated from ecosystem accounts and call for considering all the accounts to fully evaluate the environment (UN, EC, FAO, OECD, & World Bank, 2014). Although they didn't develop an integrated accounting system for the purpose yet, emergy accounting is already a viable alternative.

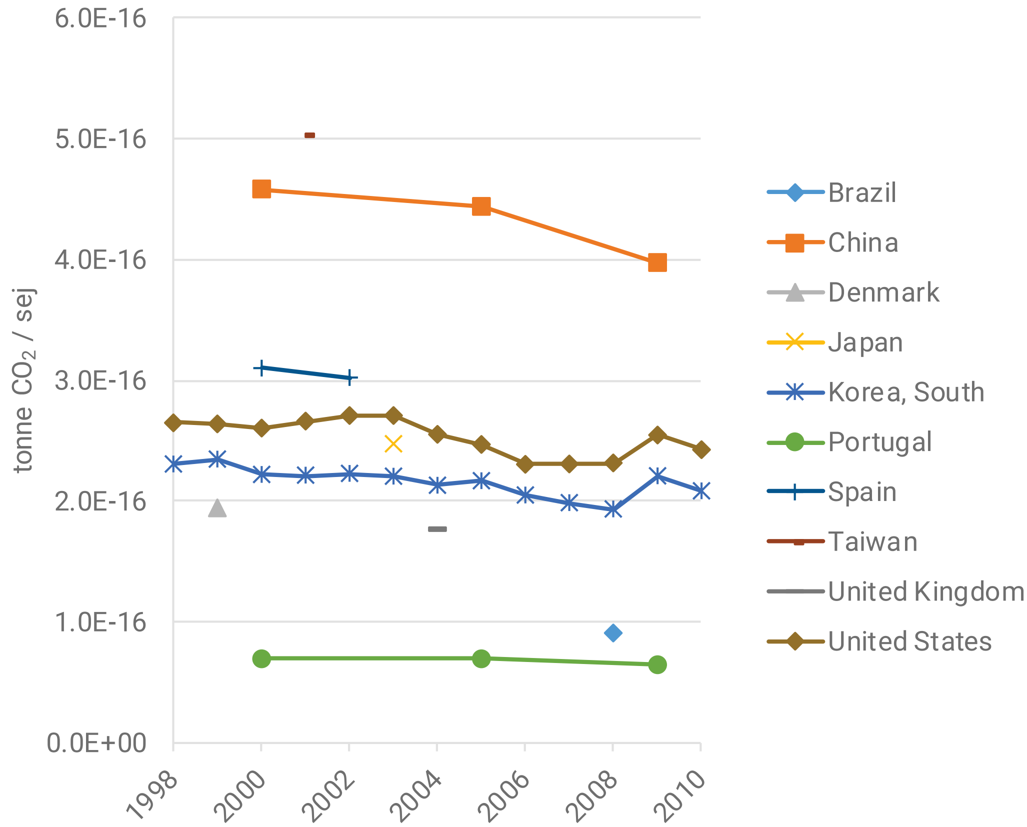
In the accounting for ecosystem goods and services, emergy has been found to be more consistent than life-cycle analysis, which is mostly based on the conventional energy accounting system (Raugei, Rugani, Benetto, & Ingwersen, 2014). Emergy accounting has been called "the most comprehensive biophysical approach for quantifying the contribution of ecosystems to economic activity" (Ukidwe & Bakshi, 2011, p. 294) by considering even the contribution of Earth's biogeochemical cycles to the environment.

4.4.1 Carbon dioxide emissions

Carbon dioxide emissions per TPES are also called carbon intensity (IPCC, 2000). Carbon intensity is not changing much in South Korea. However, CO_2 emissions per total emergy use have been slightly declining over the time (Figure 4-14). Similar trends are found in the United States, too. In the case of China, the difference is more obvious. China's carbon intensity has been rapidly increasing from 1998 to 2010. But China's CO_2 emissions per total emergy use declined over the same time frame.



a) Conventional energy accounting: CO_2 emissions per primary energy use



b) Emergy accounting: CO_2 emissions per unit emergy use

Figure 4-14: Carbon dioxide emissions per unit use of energy/emergy.
Source: This study (see Table A-11 in the appendix), EIA (2015), World Bank (2013).

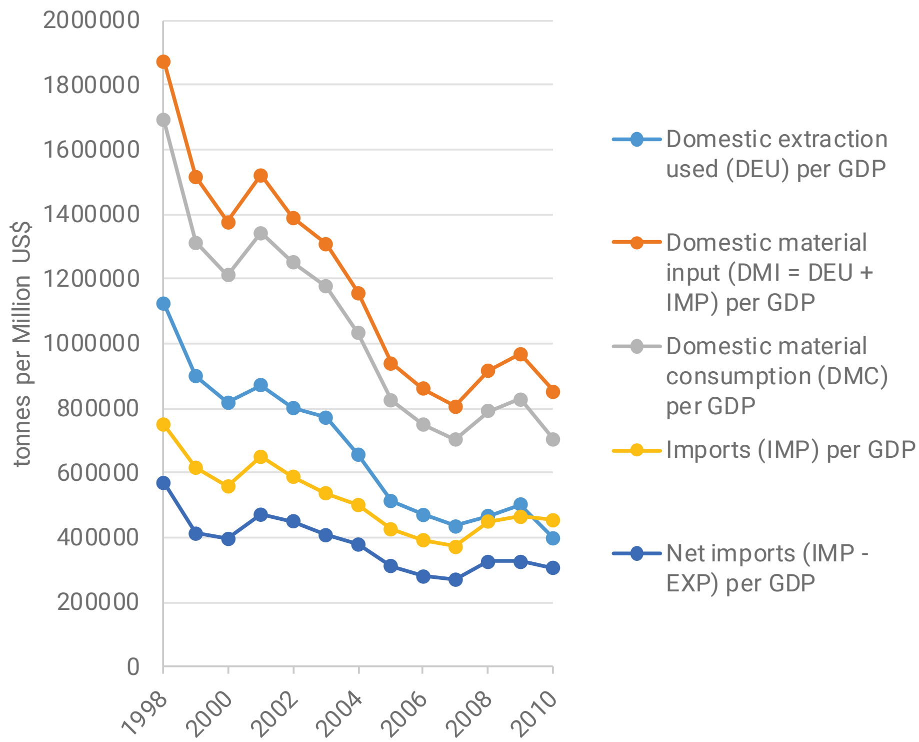
As a result, the growth of the total emergy use in those countries (South Korea, United States, and China) outpaced their TPES. In addition to energy consumption, consumption of raw materials and other commodities has increased. Because total emergy use accounts for all the inputs, its growth might be faster than the TPES growth. Then, without careful explanation, the indicator CO_2 emissions per total emergy use could mislead policymakers by showing generally declining graphs.

4.4.2 Material demand

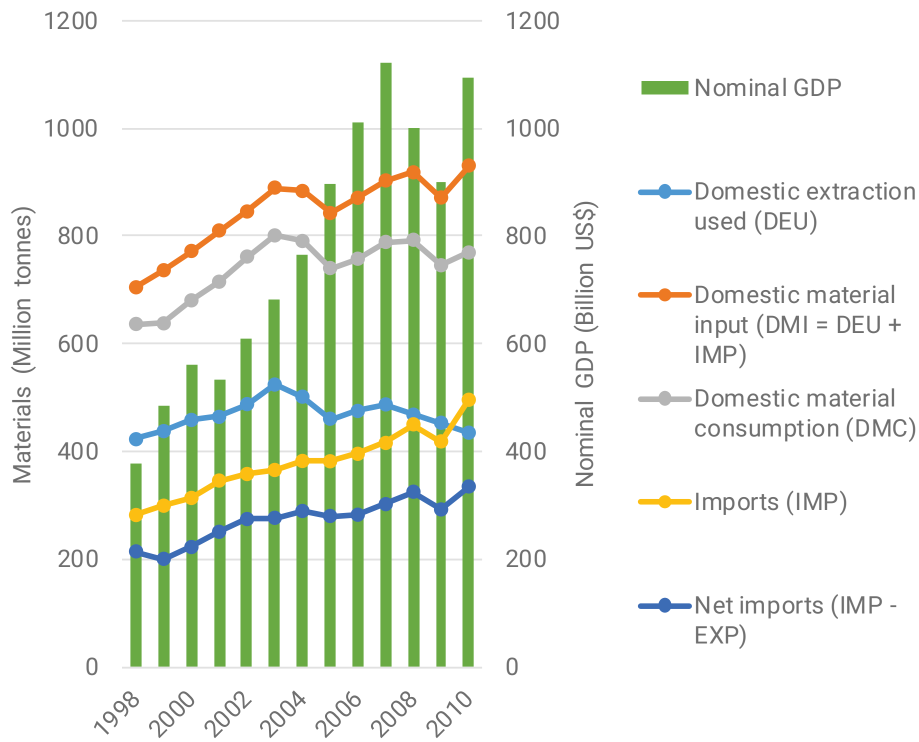
Material demand is not intrinsically covered by conventional energy accounting. But material flow analysis utilizing conventional accounting methods (known as material flow cost accounting) has been gaining support for sustainability from companies being adopted as an international environmental management accounting standard (ISO 14051) (Christ & Burritt, 2014).

But simple quantitative accounts of materials cannot easily explain a country's environmental burden caused by development or trade. Using Raw Material Equivalents (RME) is an attempt to mimic emergy accounting in material flow analysis by European Union (Schoer et al., 2012). However, even the EU admits that RME does not count raw materials' different environmental impacts and wants to explore a composite resource index that addresses the shortcomings of RME and substitute it (DG Environment, 2013).

Emergy accounting could be recommended as a national standard to promote national sustainability. Thermodynamic accounts (such as in emergy or exergy units) offer better measures of sustainability than raw material accounts by providing more accurate environmental and economic values of different materials (Valero, Valero, & Calvo, 2015).



a) Material demand per unit GDP



b) Change in total material demand and GDP

Figure 4-15: Limitations of conventional material demand statistics in South Korea. *Source:* This study, OECD (2015a).

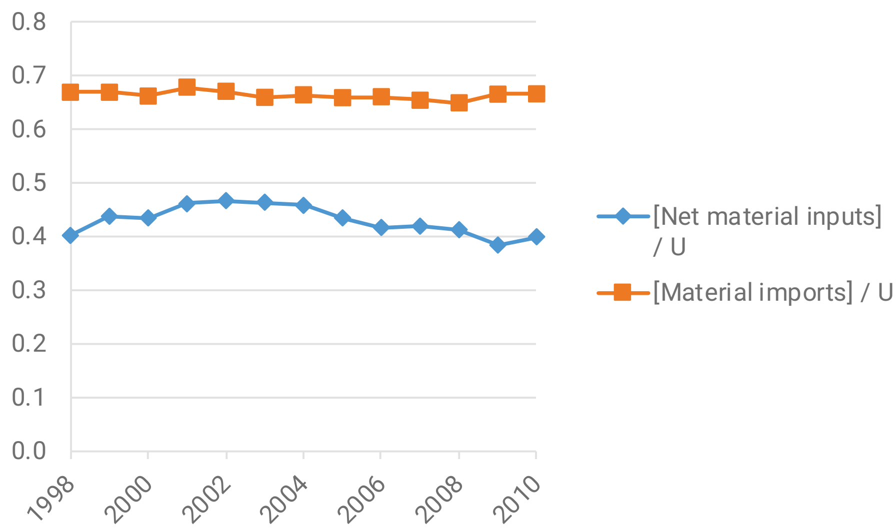
For material demand of South Korea, emergy accounting is not compared with energy accounting. In this particular comparison, the conventional accounting methods of material demand are adopted from the statistics used by both the Korean government and the OECD (Figure 4-15).

The conventional material demand is just a simple sum of all the material demand. No weighting is applied to the statistics of different materials. This indiscrimination of materials is the same, whether it is domestic extraction used

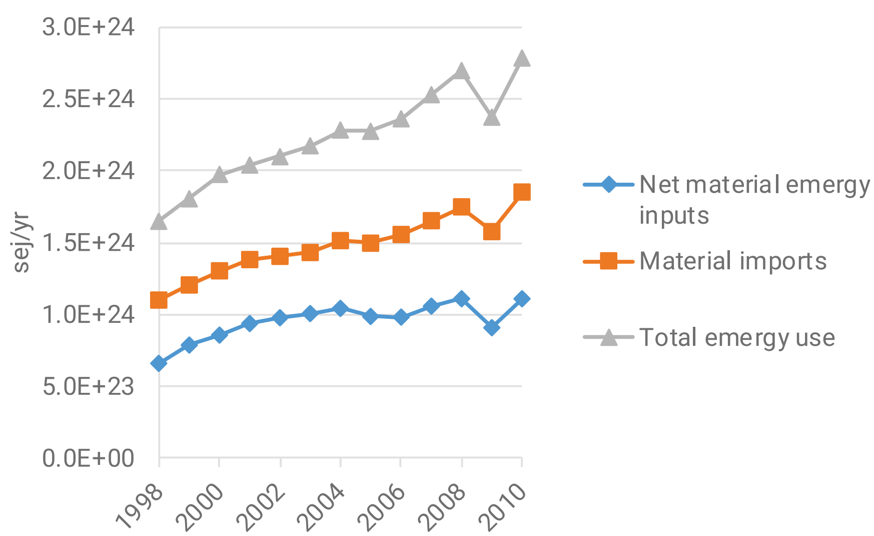
(DEU), domestic material input (DMI), domestic material consumption (DMC), material imports, or net material imports.

Emergy accounting applies unique transformities to each material. If more biophysical resources are invested in making a certain material, the emergy accounting multiplies the quantitative demand of the material by a larger transformity. If another material is made by a simple biogeochemical process and can be easily delivered to consumers, the material's consumption is multiplied with a smaller transformity. Therefore, the total material demand of a country in the emergy accounting is the sum of materials each of which is added with different weights (i.e., transformities).

That's why the time series statistics for the material demand per unit of GDP look very different from the material emergy demand per unit of total emergy use ("U") (Figure 4-16). The conventional accounting shows rapidly declining trends for the material demand per unit of GDP. However, according to the emergy accounting, neither the 'net material inputs per U' nor the 'material inputs per U' change much from 1998 to 2010.



a) Material emergy demand per unit emergy use

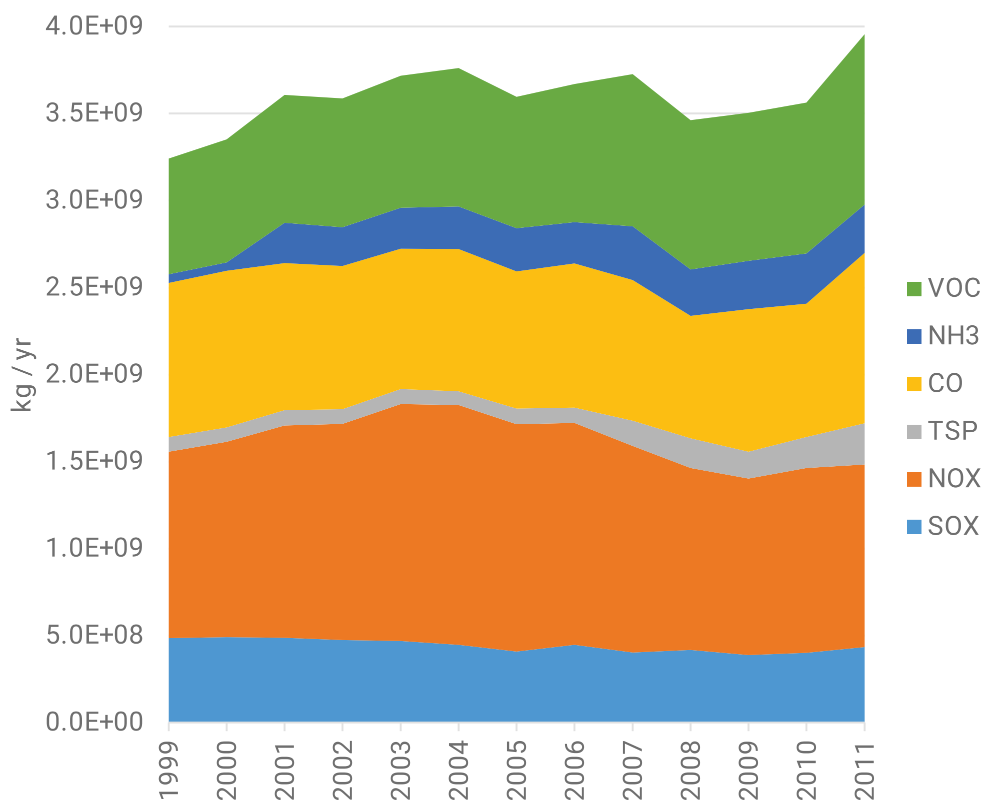


b) Change in total material emergy demand

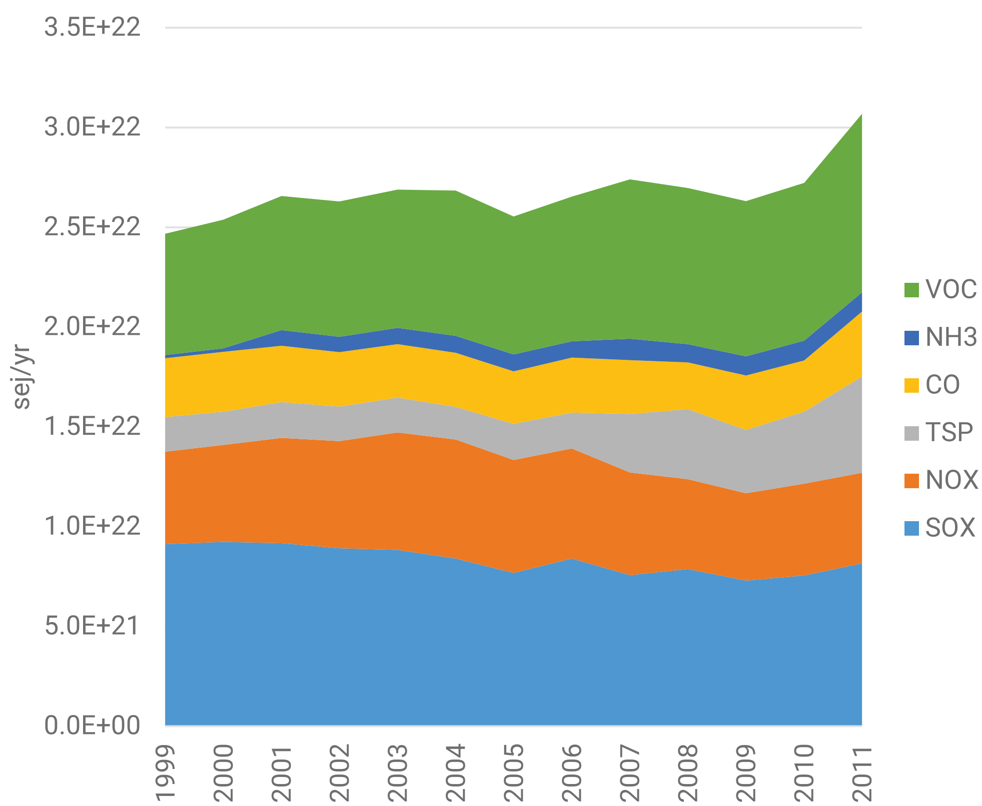
Figure 4-16: Emergy in material demand in South Korea.
Source: This study, OECD (2015a).

4.4.3 Air pollution

The same comparative merit of emergy accounting can be said of air pollution statistics. The conventional statistics of air pollution is simply adding up the weight of each pollutant's emissions (Pane 'a' of Figure 4-17).



a) Conventional statistics: air pollutant emissions



b) Emergy accounting: emergy of air pollutant emissions

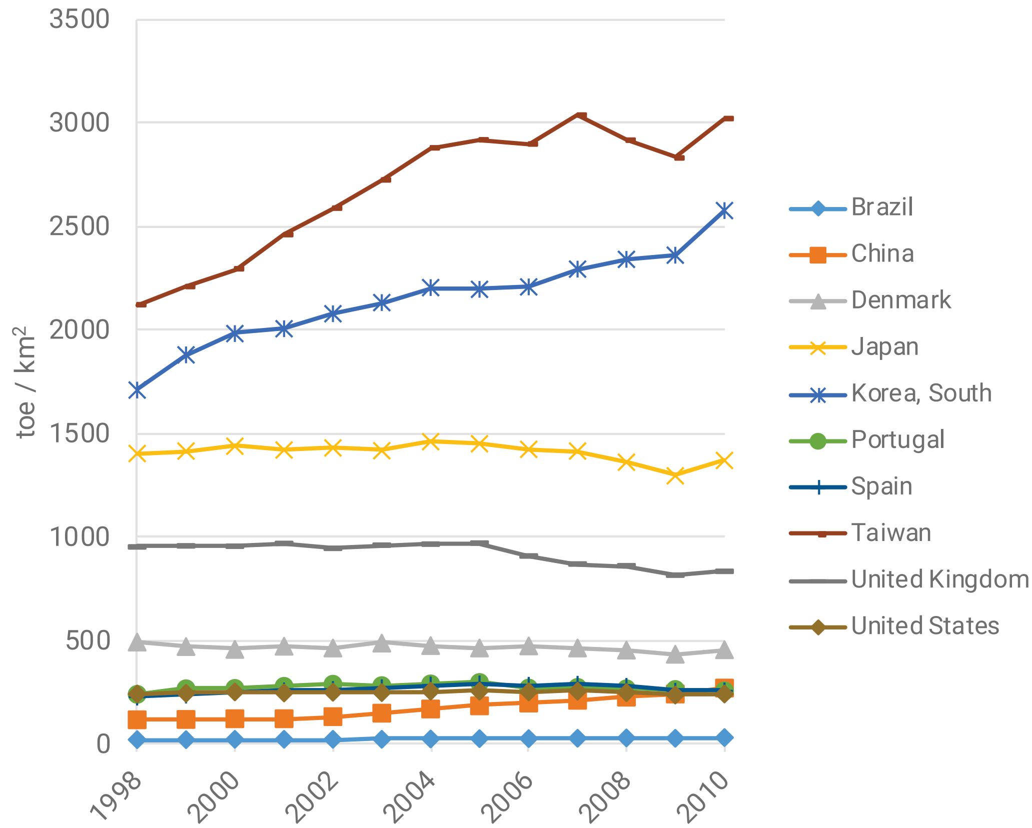
Figure 4-17: Air pollutant emissions in South Korea.
Note. Transformities of each air pollutant is presented in the appendix (Table A-10).
Source: This study, MOE (2014a).

The Ministry of Environment's Environmental Statistics Yearbook provides statistics for annual emissions of air pollutants (SO_X, NO_X, TSP, PM_{10}, CO, VOC, NH_3) and greenhouse gases (CO_2, CH_4, N_2O, HFCs, PFCs, SF_6), and annual discharge of water pollutants (industrial waste water, night soil, livestock manure) (MOE, 2013). But those quantitative values without additional information about the degree of toxicity among pollutants cannot easily present people with information about how the emissions and discharges collectively affect the overall environment. One thousand kilograms of the volatile organic compounds (VOCs) emissions cannot be the same as one thousand kilograms of sulfur oxides (SO_X) emissions. In consequence, in the conventional accounting, the sum of air pollutant emissions does not offer much meaning.

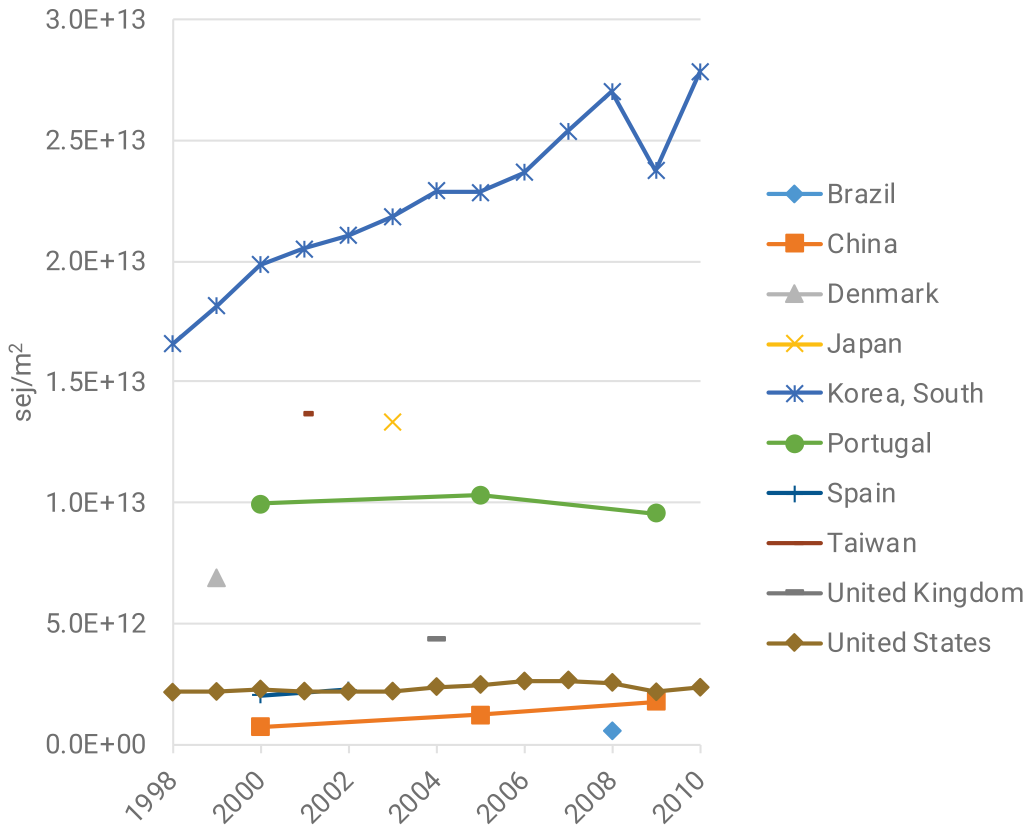
In the emergy accounting, all air pollutants have their own transformities. Therefore, each pollutant's emissions measured in solar emjoules can show how much environmental burden the pollutant imposes in a country. The more emergy a pollutant's total emissions possess, the more energy and resources are required to clean it up. As Figure 4-17 (Pane 'b') indicates, VOC and SO_X emissions constituted the largest environmental burden in 2011 (29.1% and 26.6% of the total air pollution in the emergy accounting, respectively). Shares of NO_X and CO emissions were relatively smaller in emergy accounting (14.8% and 10.7% of the total emissions in 2011, respectively), whereas the conventional accounting signaled the bigger impacts from their emissions (26.5% and 24.8% in 2011, respectively).

4.4.4 Environmental burden

The conventional energy accounting clearly shows that South Korea is consuming the second most energy per unit land area, only exceeded by Taiwan (Pane 'a' of Figure 4-18). Considering the environmental effects of energy consumption, especially that of fossil and nuclear energy, the TPES per land area can be an indicator of environmental burden.



a) Conventional energy accounting: primary energy supply per unit area



b) Emergy accounting: emergy use per unit area

Figure 4-18: Energy/emergy use per unit area.
Source: This study (see Table A-11 in the appendix), BOE (2013), DGBAS (2013), World Bank (2013).

But the total emergy use per land area provides more information. Because South Korea is over-exploiting not only energy but also other resources (Pane 'b' of Figure 4-18), the country's emergy use per land area is by far greater than that of the other nine countries, including the most TPES-intensive Taiwan. And the emergy use intensity is getting worse at an average annual grow rate of 4.4% from 1998 to 2010. China's emergy use intensity growth, the CAGR, which is 10.6% from 2000 to 2009, is faster than that of South Korea, but the absolute level was still only 7.5% of South Korea's in 2009.

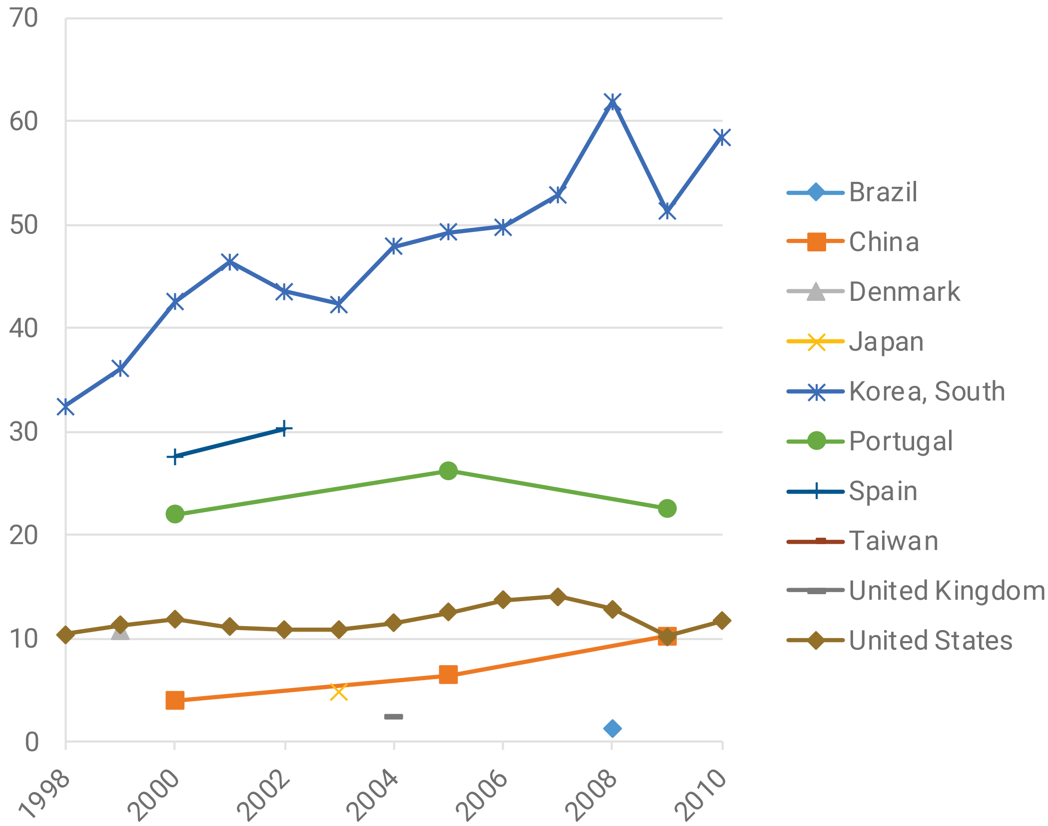


Figure 4-19: Environmental Loading Ratios (ELRs) in countries.
Source: This study (see Table A-11 in the appendix).

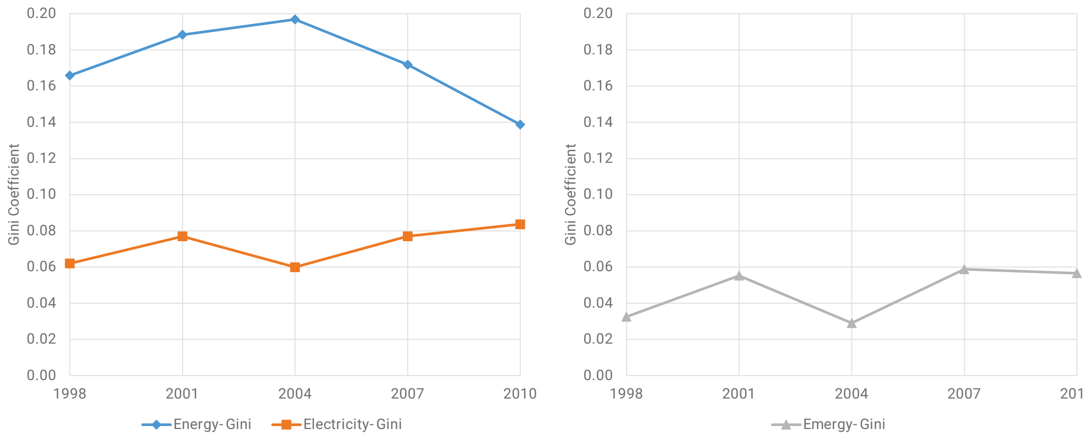
The Environmental Loading Ratio (ELR) reaffirms South Korea's heavy and worsening environmental burden (Figure 4-19). A country's ELR measures the ratio of the sum of imported and nonrenewable emergy to the total renewable emergy. South Korea's ELR was already number one among the ten countries in 1998. But it kept increasing and the 2010 ELR was 1.8 times the 1998 level. The CAGR of South Korea's ELR from 1998 to 2010 was 5.04%. China's ELR growth over 2000-2009 was 10.94%. However, China's ELR is still not comparable to South Korea's environmental burden. Korea's ELR was 51.3 in 2009, while China's ELR was 10.21 in the same year. Rather, China's ELR was similar to the United States' ELR 10.15 in 2009.

4.5 E4-Emergy Evaluation of South Korea's Equity

4.5.1 Intragenerational equity

The emergy-Gini analysis in this study has a limitation. Ideally, emergy-Gini should have been calculated from the entire expenditure of households. Due to insufficient data, however, this study calculated the emergy use by different income groups only from their energy consumption data. With the limitations in mind, analysis results of intragenerational equity are discussed.

The comparison in Figure 4-20 shows that the emergy-Gini coefficients are at the lowest levels throughout the study period, as compared to the energy-Gini and electricity-Gini coefficients. This result reveals that households with varying incomes are using a similar amount of emergy for their energy consumption despite the vast income disparity between income groups. This seemingly strange 'more equal' emergy consumption of both poor and wealthy households than by energy accounting can be explained by the concepts of 'necessity goods' and 'luxury goods.'



a) Conventional energy accounting: Energy-Gini and electricity-Gini coefficients

b) Emergy accounting: emergy-Gini coefficients

Figure 4-20: Energy/emergy-related Gini coefficients.
Source: This study, KEEI (2000, 2003, 2006, 2009, 2012a).

Energy as a necessity good (as an opposite of luxury goods) makes the energy-Gini small. Electricity as a necessity good makes the electricity-Gini smaller than the energy-Gini. Appliances and other equipment running on electricity are more ubiquitous than those that require other fuels such as oil and gas (Meier et al., 2013). As Walker and Day (2012) rightly analyzed, the low value of Gini coefficients for emergy and electricity means that low income households have to give up other essentials to pay for the high-cost of energy consumption.

The even lower emergy-Gini can be explained as follows. In the emergy evaluation, the life-supporting services of nature are taken into account, while conventional energy or electricity accounting systems do not consider those essential aspects of the biophysical environment. This result is similar to the study of

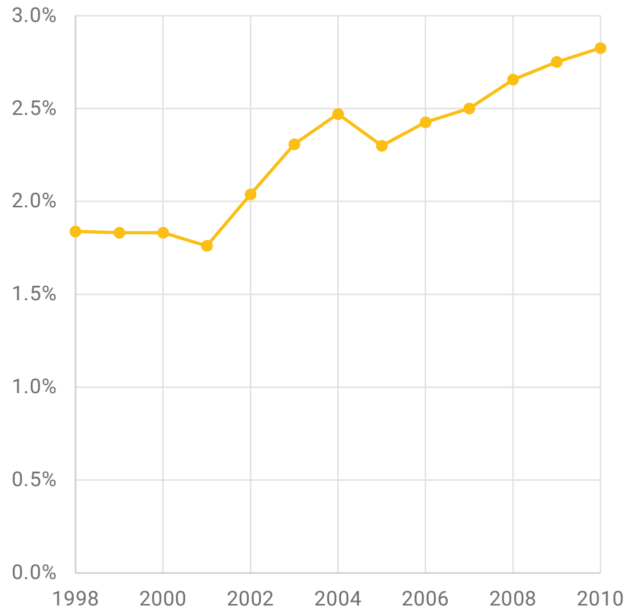
Steinberger, Krausmann, and Eisenmenger (2010) on the international material consumption distribution that showed lower Gini coefficients for domestic material consumption than the Gini coefficients for total primary energy supply. Relative to primary energy supplies, raw materials have more aspects as necessity goods.

Therefore, emergy's much stronger characteristics as a necessity good makes the emergy-Gini a lot smaller than the energy-Gini and electricity-Gini. If the emergy-Gini is so small, worsening income inequity in South Korea since the 1997 Asian financial crisis makes it much harder for poor households to maintain a comfortable daily life comprising adequate heating or cooling, cooking, and housing maintenance.

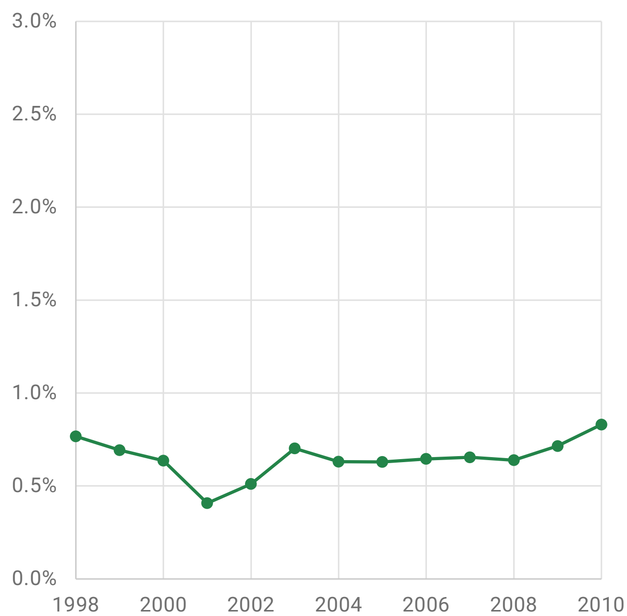
4.5.2 Intergenerational equity

The share of renewable energy in the total primary energy supply might be an energy subject. But the share of renewable sources in consumption is a very important part in a study of intergenerational equity. For example, Holden et al. (2014) state, "We use the proportion of renewable energy to total primary energy production as an indicator of intergenerational equity."

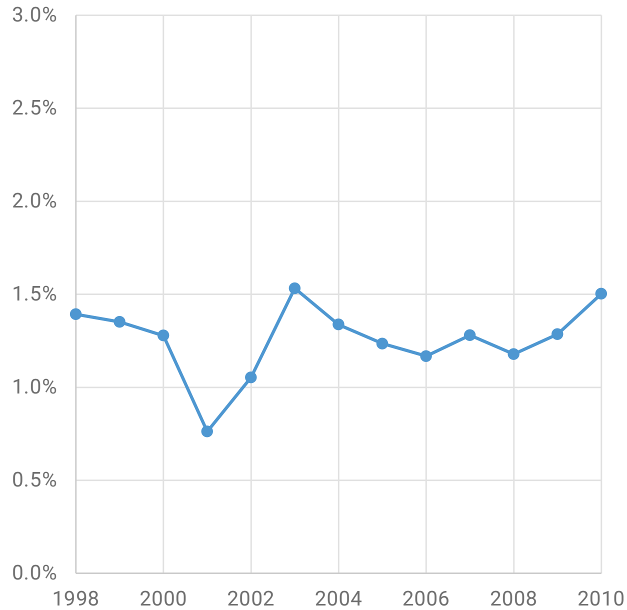
Before comparing the two accounting methods, it must be noted that there is one critical flaw about the conventional energy accounting. The Korean Government has been boasting that the share of new and renewable energy in TPES has been increasing. It is true that the sum of "new" and "renewable" energy supply has been increasing. However, the "new" energy sources are not counted as 'renewable' from international standards such as that of the International Energy Agency. If only those internationally recognized renewable energy sources are counted, the share of renewable energy in TPES goes down. And the increasing trend disappears.



a) Conventional energy accounting: new & renewable energy as a % of TPES



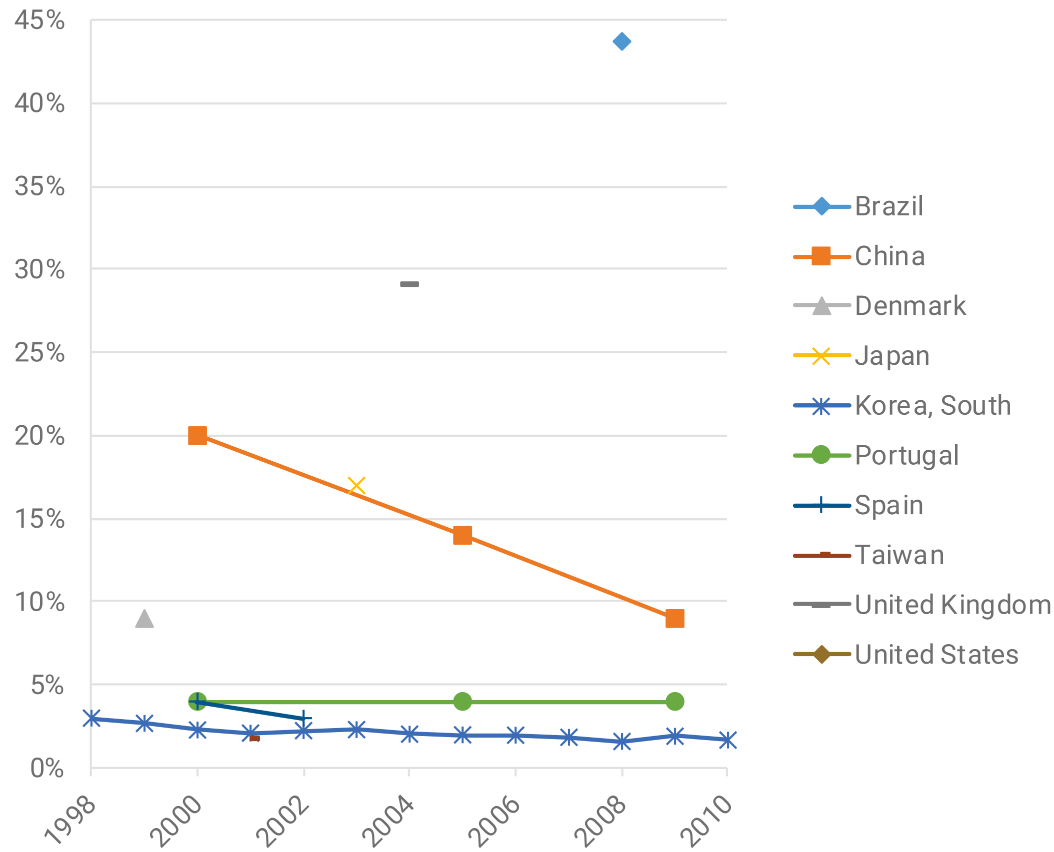
b) Conventional energy accounting: renewable energy as a % of TPES



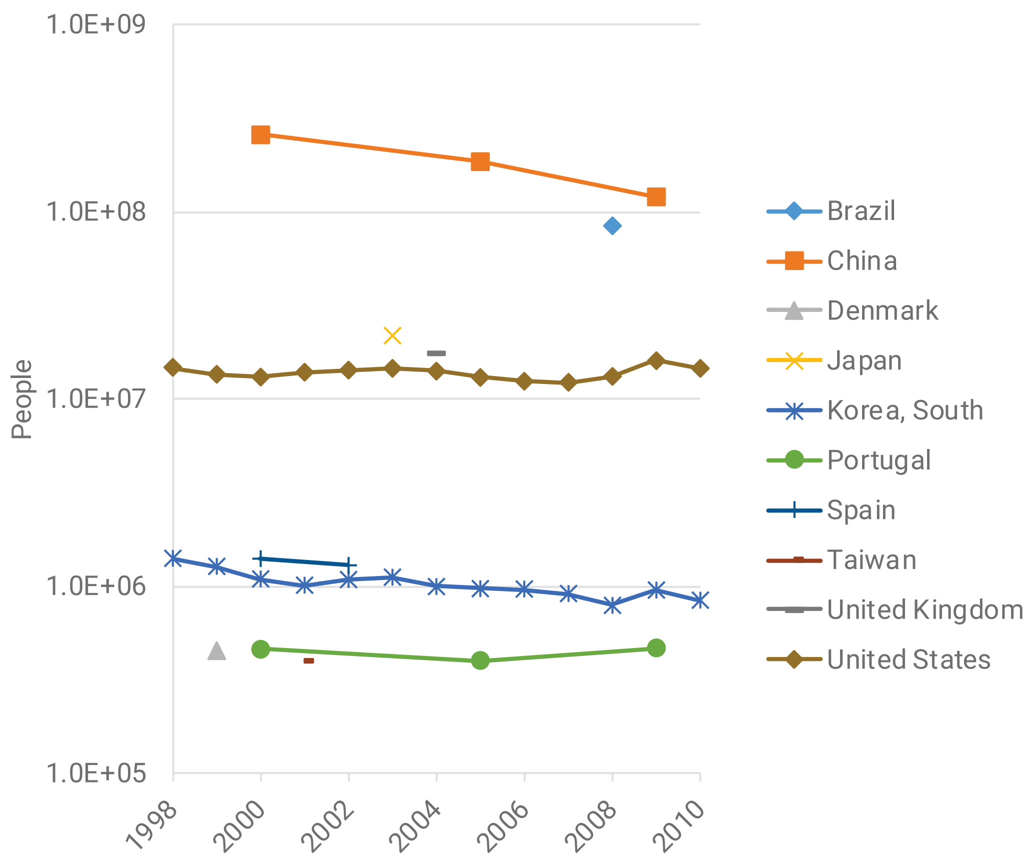
c) Emergy accounting: renewable energy as a % of total energy use (in emergy terms)

Figure 4-21: Share of renewable energy in South Korea.
Source: This study, KEEI (2012b), KEMCO (2008, 2011).

According to emergy accounting, the share of renewable energy in total energy use is slightly larger than the results in conventional accounting. But the stagnant growth of the share is almost the same (Figure 4-21).



a) Share of domestic renewable emergy in total emergy use ([locally renewable] / U)



b) Renewable carrying capacity

Figure 4-22: Renewable carrying capacity as an indicator of intergenerational equity. *Source:* This study (see Table A-11 in the appendix).

Emergy accounting gives additional information about intergenerational equity (Figure 4-22). It is the share of locally renewable emergy in the total emergy use. A very large share of renewable emergy in Brazil's total emergy use could be a good sign for the country's future generations. But only one year's indicator is not enough to draw this conclusion. For example, China's relatively high 20% share of renewable emergy in 2000 has been rapidly declining and the latest share (in 2009) was less than

10%. In South Korea, the renewable emergy share in the total emergy use was about 3% in 1998 and that has been slowly declining through 2010.

The renewable emergy shares of the countries can be translated as “renewable carrying capacity”. Because South Korea’s renewable emergy share is only 1.7% of the total emergy use in 2010, the country’s domestic natural capital can support only 0.84 million people out of 50 million total population at the 2010 standard of living. While South Korea’s total population has been increasing at an average annual rate of 0.53% over the 1998-2010 period, its renewable carrying capacity has been decreasing by 4.2% annually. Less and less natural capital is available for the country’s population. Although the decline is not only applicable to South Korea, it is not completely unavoidable. For example, the renewable carrying capacity of the United States has been almost flat with a CAGR of -0.1% over this time.

4.6 South Korea’s E4-Emergy Sustainability Progression

Radar charts are a convenient tool to visualize relative changes of a study object’s various characteristics. In emergy evaluations, an Italian scientist Sergio Ulgiati and his colleagues have used radar charts effectively (Buonocore, Franzese, & Ulgiati, 2012; Fahd, Mellino, & Ulgiati, 2012; Ulgiati, Ascione, et al., 2011). In this section, radar charts are used to summarize the E4-emergy evaluation of South Korea’s sustainability over 1998-2010 period.

Basically, one indicator was chosen from the evaluation results for each category of E4 sustainability, except for the equity pillar where both intragenerational equity and intergenerational equity are equally considered. After adding one indicator as an overall review of the assessment, the radar chart is made of six axis. They are,

- Overall sustainability indicator: ESI

- Economic sustainability: EMR
- Energy sustainability: Percent renewable in primary energy use
- Environmental sustainability: ELR
- Intragenerational equity: Emergy-Gini
- Intergenerational equity: R/U ([Locally Renewable] / U)

Two indicators (ESI and R/U) increase as sustainability improves. By contrast, the others (EMR, ELR, and Emergy-Gini coefficients) decrease as sustainability improves. To make the progression of indicators comparable, EMR, ELR, and Emergy-Gini coefficients are converted to their reciprocals. By doing so, the higher the reciprocals, the better the sustainability of the E4 pillars they represent. After the conversion, all the indicators' values for the year 1998 are normalized to one. The indicator values in 2010 are expressed by their relative difference from their past values in 1998.

The result is Figure 4-23. The overall sustainability of South Korea, as represented by ESI, is lowered by 51% from 1998 to 2010. The environmental sustainability, the intragenerational equity, and the intergenerational equity are also brought down by 45%, 42%, 44%, respectively during the same period. The economic sustainability expressed by the reciprocal of EMR seems improved by 66%. The energy sustainability also looks better in 2010 by rising 8%.

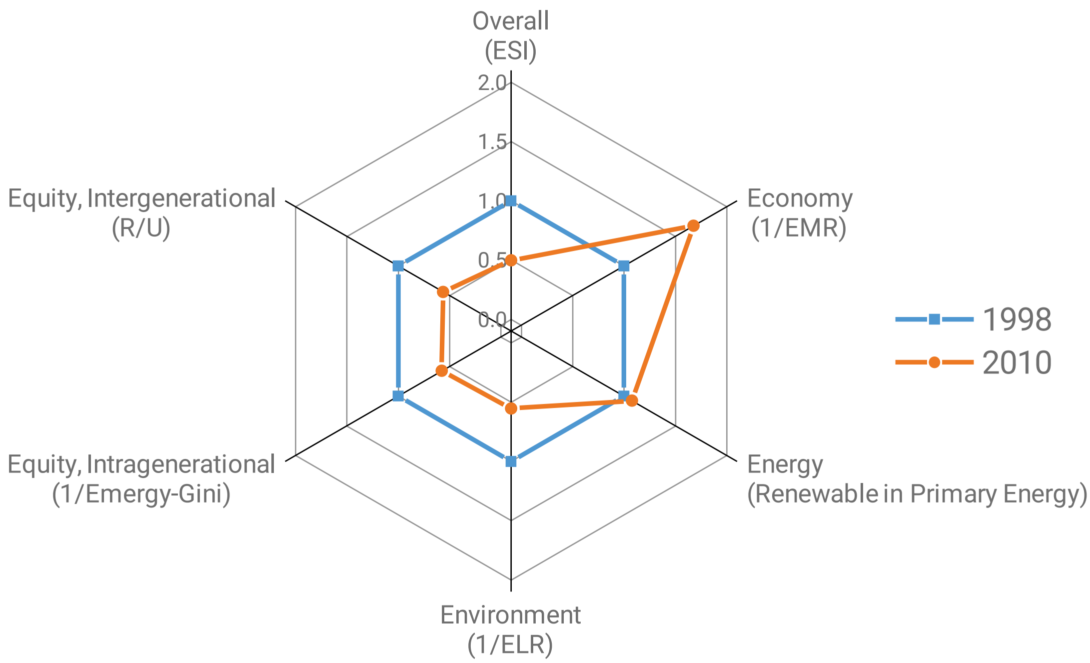


Figure 4-23: Progression of E4-Emergy sustainability.
Source: This study.

At first sight, the radar chart seems to give mixed results. For example, why did the overall indicator ESI decrease more than any other indicator? Because the positive changes in the economic and energy sustainability indicators are very small or even misleading.

In general, a country's Emergy to Money Ratio will go down as the country's economy develops. South Korea's downward EMR change (or the rise of the reciprocal of EMR) is not a bad sign. But the change is mainly due to money supply as Figure 4-6 illustrates, not because of the country's efficient use of geobiospheric resources. The share of renewable emergy in South Korea's primary energy supply is very small. It was so small in 1998 that a minuscule change in absolute number in 2010 looks slightly better than 12 years ago. Still, the 2010 values are very small.

By this integration of E4-Emergy evaluation results, it became more evident that South Korea's E4-Emergy sustainability is deteriorating rapidly. It is not that a country's sustainability which was previously sound is getting worse. The country's ESI in 1998 was already 0.04, which was lower than any ESI values of the other nine countries reviewed in this study throughout the 1998-2010 period. And the worst value went down further to 0.02 in 2010.

Chapter 5

POLICY IMPLICATIONS

Policy implications of the new explanations and insights resulting from the E4-Emergy evaluation of South Korea were identified. In this chapter, they are presented in two categories: (1) a policy implication from the comparison of conventional energy accounting and emergy accounting, and (2) policy implications from comparison of E4-Emergy indicators of South Korea with those of 9 countries.

5.1 A Policy Implication from Comparison of Conventional Energy Accounting and Emergy Accounting: Institutionalization of Emergy Accounting

The comparison of conventional energy accounting and emergy accounting revealed that South Korea's very small domestic renewable resources are being rapidly depleted. In contrast, imports of foreign nonrenewable emergy sources are increasing more than in other countries compared in the study. Two policy implications stem from this finding.

Firstly, South Korea's national accounts must reflect the flows and stocks of natural resources. Of course, natural resources that are traded in the market are already accounted for in Korea's national accounts, but non-monetary values are almost entirely neglected. Although it may not be possible to introduce emergy accounting of the resources to official national statistics, immediately, the country can begin the preparatory work by collecting necessary data to evaluate and refine unit emergy values (UEVs) of the resources.

Secondly, imported goods and services also need to be re-evaluated by emergy accounting. This task, if implemented, will be much more daunting than the emergy accounting of domestic resources. Foreign resources are more diverse in the amount of cumulative empower production than domestic resources that are produced by rather simple pathways. But it is not an impossible task, either. Global input-output models such as the Global Trade Analysis Project (GTAP) (Walmsley, Aguiar, & Narayanan, 2012) and KLEMS (K-capital, L-labor, E-energy, M-materials, and S-purchased services; for example, see O'Mahony & Timmer (2009) and Pyo, Chun, and Rhee (2012)) models are compiling a huge database of various resources. In Korea, government-funded research institutes such as KIEP and KEEI have been extensively utilizing them for their research that will be crucial for the government's decision making. And GTAP and KLEMS databases are constantly updated to reflect changes in every country's economic and resource environment. If the same level of rigor is dedicated to build an emergy database for South Korea's imports, the country will have a strong data infrastructure to formulate robust policy options.

5.2 Policy Implications from E4-Emergy Indicators of South Korea with Those of 9 Countries

The E4-Emergy evaluation results clearly show that the people and governments of South Korea are living far beyond their biophysical constraints. If a country does not live within biophysical constraints, two problems can happen. First, inevitably, the country's domestic resources will be depleted. Along the course of the depletion, social cohesion will be broken because wealthier or more powerful people might use a larger share of the remaining resources, while low income or socially marginalized people resent the systemic inequity. Second, if the country tries to postpone the resource depletion by importing more resources, it will exploit foreign lands with relatively less expensive resources. While that kind of survival strategy may work for a while, it eventually brings about conflicts between resource-importing countries (Ko, Hall, & López Lemus, 1998). Intragenerational equity problems arising from conflicts between resource-importing and -exporting countries due to carbon leakage (Marcu, Egenhofer, Roth, & Stoefs, 2013) or pollution outsourcing (Poelhekke & van der Ploeg, 2015) are additional concern.

There are barriers to achieving sustainability, whether they are psychological (Gifford, 2011) or systemic roadblocks (Beddoe et al., 2009). Especially, Robert and Zeckhauser (2011) argue that more sophisticated approaches are required for normative policies like sustainability policies. This chapter will suggest exemplary policy options for achieving each dimension of E4 framework.

5.2.1 Economy

This study's economic sustainability assessment of South Korea found that most prominent problem related to South Korea's economic sustainability is that the money supply is growing faster than the increase in total emergy use. This is similar to Sgouridis's finding (2014) between money supply and total energy consumption. According to Costanza et al. (2012), the money supply is created by the "fractional reserve banking". In modern countries, "most money is today created as interest-bearing debt." They found problems of the money-making credit system for economic sustainability are:

a. It is highly destabilizing
b. It steadily transfers resources to the financial sector.
c. Since the banking system currently creates far more money than the government, this system prioritizes investments in market goods over public goods, regardless of the relative rates of return to human well-being.

d. Debt, which is a claim on future production, grows exponentially, obeying the abstract laws of mathematics. Future production, in contrast, confronts ecological limits and cannot possibly keep pace.

To solve the problems of the fractional reserve banking systems, Herman Daly, a pioneering ecological economist and former World Bank senior economist, once called for a normative goal of a 100% reserve banking system (Daly, 2009). However, Dittmer (2015) found it very unrealistic. Because this study is not about financial system reform, the policy implication from this excessive money supply would be pointing in a direction, at most. That is, "to create a culture that restricts money and interest to their appropriate roles," as Strunz, Bartkowski, and Schindler (2015) suggested.

A promising target for realizing the culture would be a kind of "culture of descent" embedded in the vision of "a prosperous way down" proposed by Odum and Odum (2001). Although the vision is not exclusively suggested for economic sustainability, Odum and Odum are confident that a country's long-term sustainability cannot be achieved if the country continues to synchronize its entire system with the market. There are many components of South Korea that are parts of the production and use of emergy but operate and circulate apart from money (Odum & Odum, 2001, pp. 91-92). Sustainable emergy use cannot keep up with economic growth based on money supply. Although there might be a period of growth, the sustainable society or country will follow a series of succession and adjust itself down to a state that requires less emergy use. If South Korea wants to promote real economic sustainability in this "culture of descent", it will have to significantly revise its habit of increasing money supply apart from total emergy use. Keeping the separation of commercial banks and investment banks and suppressing investment banking activities would be one of no-regret policies in Korea (Dow, Johnsen, & Montagnoli, 2015).

Although macroeconomic impacts like reduction in the money supply are doubtful (Michel & Hudon, 2015), positive effects of alternative money supply or complementary currency circulation by bottom-up grassroots efforts, such as local economic development and building social capital, have been confirmed even in developed countries (Seyfang & Longhurst, 2013). Local currencies, community currencies or time banking credits, and alternative money supplies will be very helpful to ensure such cultural change as endorsed by Strunz et al. (2015) or Odum and Odum (2001).

5.2.2 Energy

The top priority of South Korea's energy policy must be reducing the share of purchased foreign emergy. The reduction of foreign-born emergy must entail policies for raising the share of renewable energy.

In addition to large-scale renewable energy development policy such as the government's Renewable Portfolio Standard (RPS) policy, small scale renewable energy promotion measures must be reinforced. Since the government replaced the feed-in tariff (FIT) scheme with the RPS in 2012, financial sustainability of small scale renewable energy has declined as small generators could not compete against large providers in the Renewable Energy Certificate (REC) market (H. Choi, 2014; Kwon, Kim, & Shin, 2014; T. Lee, Lee, & Lee, 2014; Yoon & Sim, 2015). While the 13 big utilities-driven renewable energy development has merits like lower system cost with economies of scale, the lack of small scale development can lose the advantage of distributed generation such as less transmission line requirements and lower environmental impacts. In addition, most of the utilities with RPS requirements are government-owned, they seem to assume that the noncompliance penalty or purchasing cost of RECs will be eventually exempted or paid with taxpayer money. Renewable energy development was not their first concern and so no public utility has met the RPS requirements in the first year of implementation (See Table A-11 in the appendix). As Seoul has shown by its success in residential solar PV installation with its own FIT program (SMG, 2014), there must be fixed price payment for small scale renewable energy providers.

Renewable energy policies cannot succeed without local stakeholders' input and acceptance (Wolsink, 2010). This process of adaptive co-management can only happen when the central government endows substantial independence to local governments. Although it has been 20 years since local governments were first elected by their constituents in June 1995 (J.-W. Choi, Choe, & Kim, 2012), their fiscal independence is still very weak. The national average of local government's financial independence has been declining over the past 15 years. In 2015, local governments could provide only 45% of their financial needs from internal revenues. In consequence, more than half of their finance is funded by the central government (Figure 5-1). These fiscal constraints must be relaxed in order to promote active cooperation between governments and allow fine-tuning policy along with implementation.

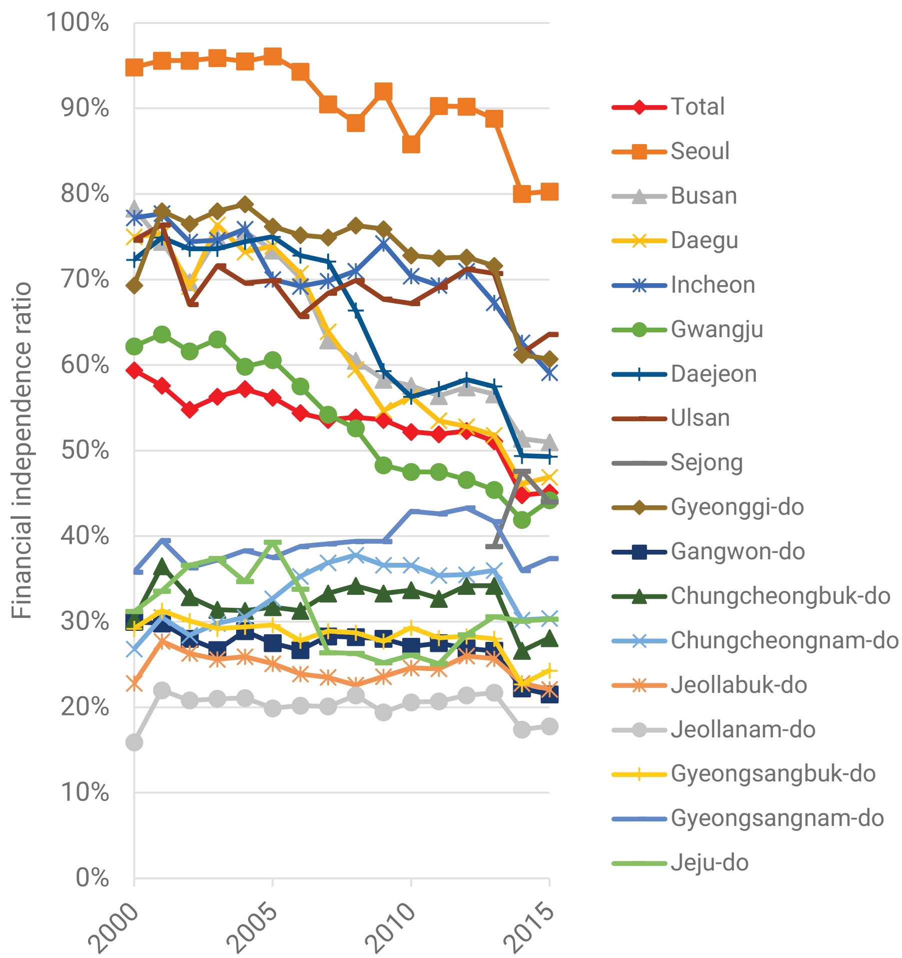


Figure 5-1: Declining financial independence of local governments.
Note. [financial independence ratio of local governments] = ([local tax] + [non-tax revenue[4]]) / [general account budget] × 100.
Source: MOGAHA (2015).

[4] [**Non-tax revenue**] = [**current non-tax revenue** (property rent revenue, charges, fees, business operating revenue, collection grants revenue, interests, etc.)] + [**temporary non-tax revenue** (property disposal revenue, revenue from previous year, deposit & expect collection, loan collection, allotment, etc.)] (MOGAHA, 2014).

Once the governance problem is addressed, there is much space for local communities. Local "communities are more likely to support energy systems that they have a stake in." (Sovacool, 2011) In that regard, renewable energy cooperatives are one promising source of renewable energy promotion (Frantzeskaki, Avelino, & Loorbach, 2013; Hoppe, Graf, Warbroek, Lammers, & Lepping, 2015; Huybrechts & Mertens, 2014; Kunze & Becker, 2015; Ruggiero, Onkila, & Kuittinen, 2014). Because local people have relatively closed-access to resources, institutions and markets can be cooperative (Pretty, 2003), renewable energy cooperatives can find best-fitting practices for specific communities more efficiently.

5.2.3 Environment

South Korea is relying on imports both for energy resources and non-energy resources such as minerals and other commodities. This dependence inevitably resulted in both the emergy use per unit area and Environmental Loading Ratios (ELRs) of South Korea being the highest or one of the highest among the 10 countries compared in this study. Furthermore, these indices are getting higher over the study period (Section 4.4.4).

It is true that South Korea is heavily dependent on imported energy (Gnansounou, 2008; Gupta, 2008; Robertson & Robitaille, 2014). However, this study found that South Korean people were consuming non-energy resources less efficiently than they were consuming energy resources (Section 4.2.1). The material emergy demand per unit emergy use (Section 4.4.2) shows that there has been no improvement in the efficiency of material consumption. In addition, this vulnerability of South Korea is not predestined but self-induced, because the country is more dependent on imported emergy than similarly resource-poor countries such as Japan and Taiwan

(Section 4.2.2). This study also found that the majority of South Korea's imported emergy is consumed internally. This consumption pattern is closer to Japan's than China's (Section 4.2.3).[5]

Then South Korea's domestic use of non-energy emergy imports could be a priority target of environmental sustainability policies. What could be the instruments to solve the problems?

Although technological progress might solve South Korea's problem of depleting domestic resources and heavy dependence on imported resources in the future, the level or speed of progress is not known yet. So the country must act to smooth out the transition into the scarcity or depletion stage as shown by Odum and Odum (2001) and Gunderson and Holling (2002). Giljum and Hinterberger (2014) pointed out that the problems will hurt South Korea's sustainability in two ways: biotic and abiotic resource scarcity. Biotic resource scarcity will greatly reduce the ecosystem services as accounted by the United Nations (Millennium Ecosystem Assessment, 2005). Abiotic resource scarcity will hurt the country's industry. Among the policies they suggested for resource sustainability, the most relevant ones for this study are as follows.

Giljum and Hinterberger (2014) recommended for comprehensive measurement of resource use at product, company, and industry levels. In that case, emergy evaluation with its solar emjoule unit and key indicators is a very good measuring tool. This bottom-up measurement of micro- and meso-level resource use

---

[5] Some parts of these findings are from sections for the economic sustainability evaluation (Sections 4.2.1, 4.2.2, and 4.2.3). But the policy implication applies to this environmental pillar of the E4 sustainability.

in emergy terms will significantly improve the understanding of people and the government about their real resource use.

They also called for the promotion of the circular (recycling; or sustainable consumption and production) economy, where “resources are routinely recycled, reused, converted, upgraded, and stored for future use.” For the circular economy, emergy evaluation has already been found to be a very good tool, because a “supply-side” emergy-based indicator approach helps track the entire “production cost” (Geng, Sarkis, Ulgiati, & Zhang, 2013). A major source of South Korea’s non-energy emergy consumption seems to originate from constructing new buildings. South Korea’s material consumption for building is higher than most countries, being the 10th largest consumer of construction materials in the world in 2008 (Wiedmann et al., 2015). As Steger and Bleischwitz (2011) found from their EU study, new dwellings drive material consumption. Because the fast increase in the residential area per person is observable in Table 5-1, South Korea has built bigger and bigger residential buildings.

One more policy suggestions from Giljum and Hinterber (2014) is stronger diversification of economies. This could mean many things, but for South Korea, a transition from a product-ownership economy to either a sharing economy (Belk, 2014) or a service-consumption economy (Bellos & Ferguson, 2015) could be an option.

Table 5-1: Residential building areas per household in South Korea

	1980	1990	2000	2010
Area per household (m^2)	62.8	86.1	81.9	94.2
Household size (people)	4.5	3.7	3.1	2.7
Area per person (m^2)	14.0	23.3	26.4	34.9

Source: Lee (2013), Statistics Korea (2015b).

5.2.4 Equity

5.2.4.1 Intragenerational equity

There is a visible spatial distribution in household disposable income in South Korea. Because of the poverty trap effects of the spatial segregation (Meen, 2009), local or community-driven efforts cannot deal with low income households' emergy affordability issues. Thus, intragenerational equity is the part of E4 sustainability where a top-down policy is more effective in the short term, rather than bottom-up approaches.

According to OECD statistics, South Korean government has not devoted resources to resolve the intragenerational equity problem. Figure 5-2 shows shares of social spending in each country's GDP. Korea has the second smallest share of social spending among OECD countries.

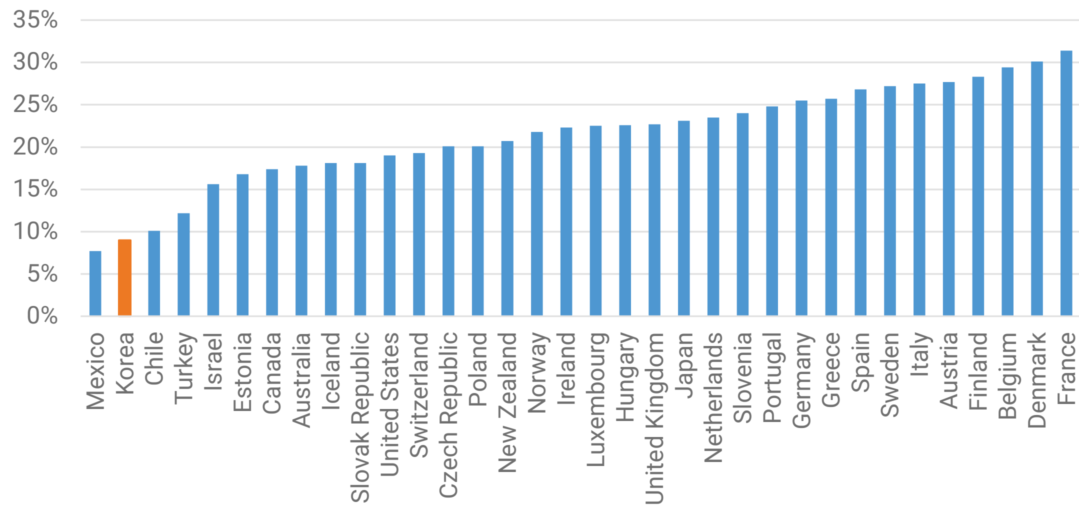


Figure 5-2: Public Social Expenditure as % of GDP, 2011.
Source: OECD (2015b).

As a result, public spending has hardly reduced income inequality in South Korea. Figure 5-3 indicates how much income inequality (Gini coefficient) was reduced by taxes and cash transfers in 2011. Korea is again the second worst country in reducing income inequality by those measures.

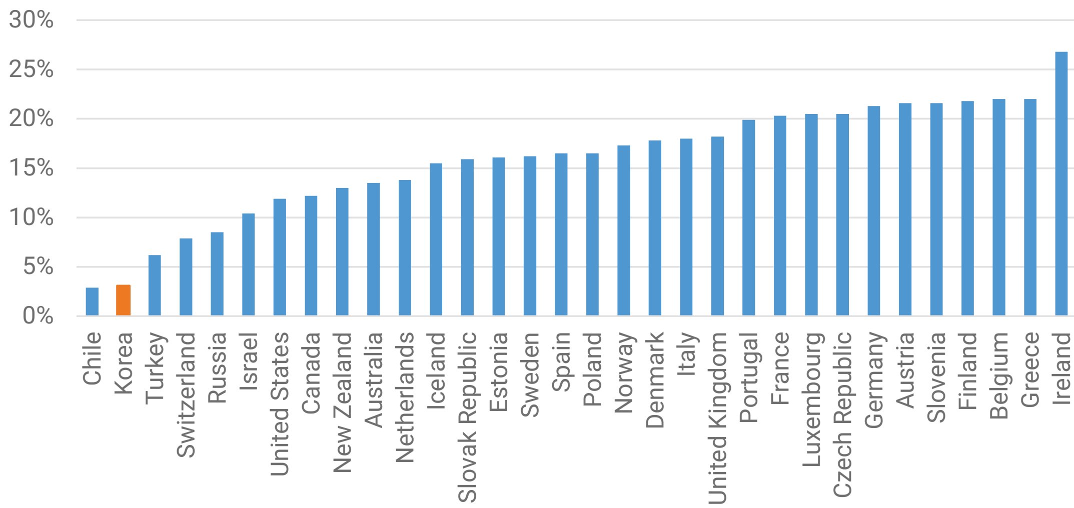


Figure 5-3: Effects of taxes and transfers on the percentage point reduction of the Gini coefficient for market income, 2011.
Note. 2010 data are used for Australia, Netherlands, Russia, and United Kingdom.
Source: OECD (2015b).

What can be done to remedy these symptoms? South Korea can pursue two options. First, the country can expand current public energy welfare policies for low income households. For example, the South Korean government and public utilities are providing low income families with energy efficient facilities and products (energy efficient lamps, residential weatherization, etc.), energy cost discounts (electricity, city gas, heat), and energy vouchers (heating oil voucher, briquette coupon, comprehensive energy vouchers) (H. J. Lee, Park, Park, Han, & Jun, 2013).

Second, if South Korea can go further, the country could significantly increase social expenditures, not only the absolute amount, but also as a percentage of her GDP. It has been proven that "no matter where you live, social spending will reduce the probability of poverty" (Zwiers & Koster, 2015). In this direction, South Korea can begin with a minimum pension guarantee policy (Atkinson, 2015). The reason for this suggestion is that among the OECD member countries, South Korea's poverty rate (14.9 %) is relatively high, ranking 7th among the 34 countries. However, old age poverty rate (47.2 %) is overwhelmingly higher than that of the other members. Even the second highest poverty rate (35.5 % of old people in Australia) is more than 10 % lower than that of Korea (Figure 5-4). To make the problem worse, Korean retirees have the second smallest share of income received from public pensions (Figure 5-5). While income inequality is an intragenerational equity issue, old age poverty must be addressed as an urgent problem from both intra- and inter-generational equity perspectives.

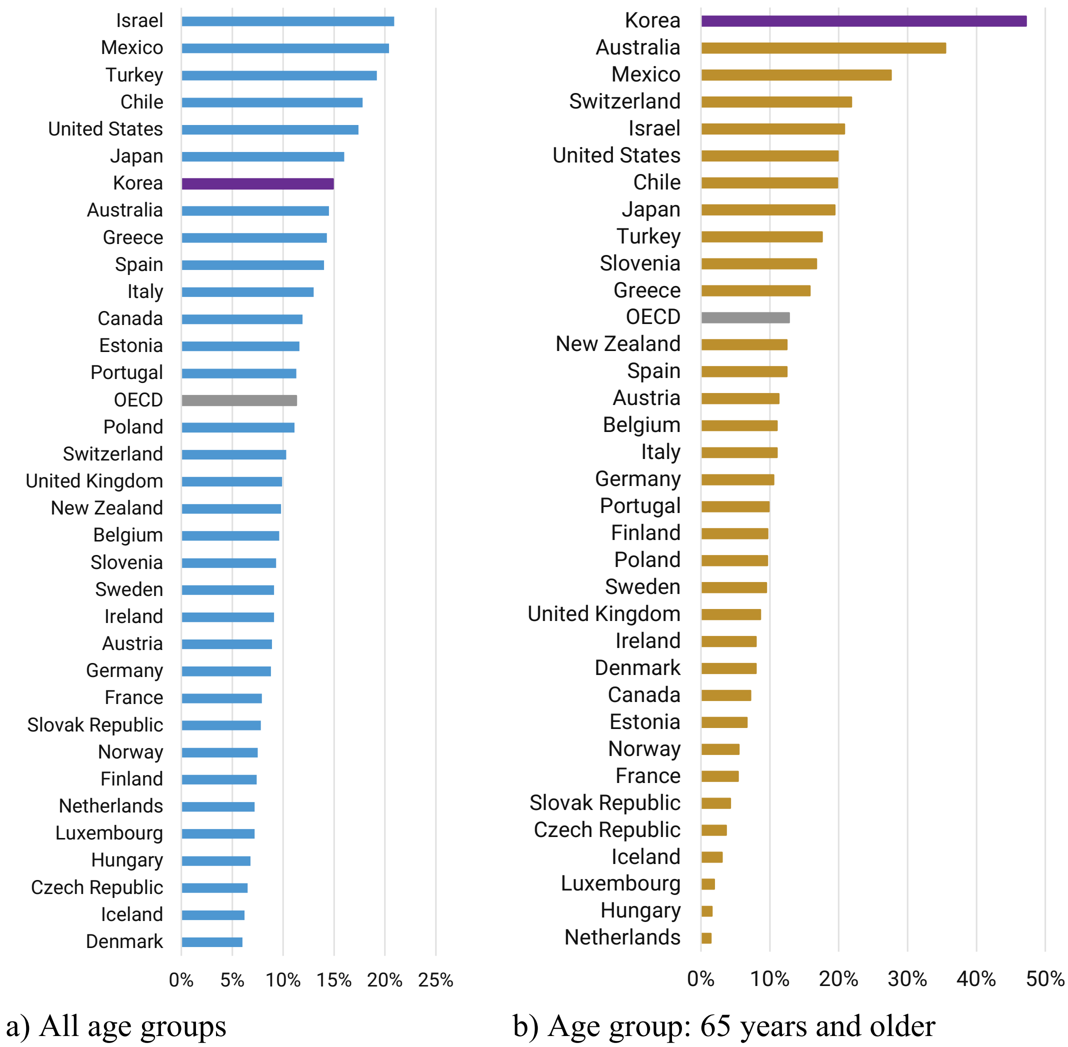


Figure 5-4: Poverty rate after taxes and transfers.
Source: OECD (2013).

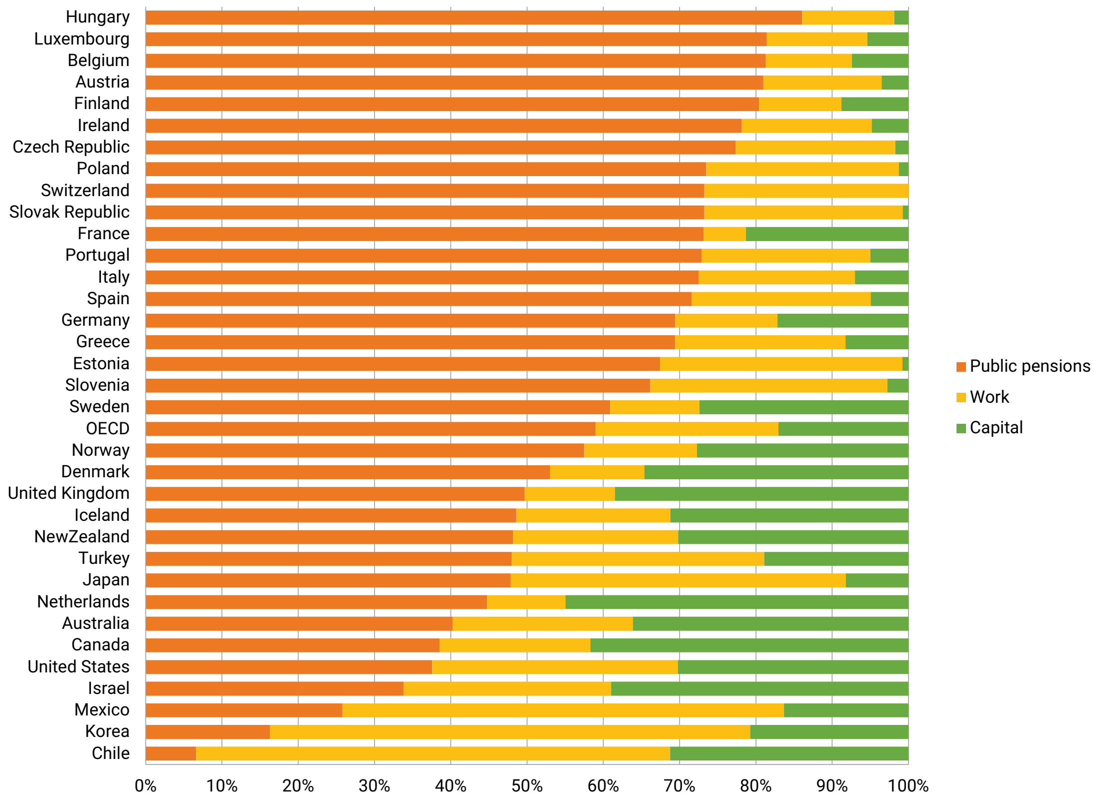


Figure 5-5: Sources of incomes of the over 65s, late 2000s.
Note: Public pensions = earnings-related benefits + resource-tested benefits; income from work = employment income + income from self-employment; capital income = private pensions + income from returns on non-pension savings.
Source: OECD (2013).

5.2.4.2 Intergenerational equity

Baumgärtner, Klein, Thiel, and Winkler (2015) empirically showed that rapidly declining ecosystem services means a strong need for a significantly lower social discount rate for ecosystem services than manufactured goods. If it is accepted that the renewable emergy flows are a proxy for ecosystem services as suggested by Coscieme et al. (2014), South Korea's decline in the indicator inevitably calls for a very low social discount rate, which means the country needs either unusually high precautionary savings of ecosystem services or has to place relatively higher weights on future generations than other countries.

If a country aims for higher economic growth, the social discount rate cannot be brought down (Steinbach & Staniaszek, 2015). If South Korea decides to discard the growth-oriented development goals and adopt sustainability-driven objectives, there is a chance for intergenerational equity in the country with the following suggested policy change. To ensure a larger probability of future generations' welfare, the lowest possible social discount rates should be adopted for feasibility assessment of any development proposal that might undermine natural resources. The current social discount rate of 5.5% that has been used by the Korean government (Ahn et al., 2008) cannot encourage such resource management behavior that promotes intergenerational equity. As Table 5-2 indicates, if the 5.5% discount rate is adopted, the economic losses that people in 64 years (the current generation's grandchildren) will suffer from natural resource depletion is considered as only 3% of the value of the environmental benefits which people are now enjoying.

If Stern Review's recommended discount rate 1.4% (Stern, 2006) is demanding an abrupt change from 5.5%, South Korea can begin with current best practices of Germany (3%) or Norway or the United Kingdom (3.5%) discount rate (Vardakoulias, 2013). If South Korea can go further, the country can adopt a declining discount rate scheme on top of the best practice rates (Arrow et al., 2014).

This policy direction has additional benefits for future generations. The lower social discount rate is, indeed, inducing lower private discount rates (Elliston, MacGill, & Diesendorf, 2013) and subsequently faster deployment of renewable energy technology by providing favorable financing environment (IEA & NEA, 2015; Zweibel, 2010).

Table 5-2: Present value of 1% reduction of South Korea's 2010 GDP by natural resource losses after two generations

Discount rate (per year)	Present value [a] in 64 years [b] (million US dollars)	Difference ([present value at 0% discount rate] = 100)
0%	10,147.00 [c]	100
1.4%	4,167.82	41
3%	1,530.22	15
3.5%	1,122.42	11
5.5%	329.75	3

[a] $[\text{Present value}] = [1\%\ \text{of GDP}] \times \left(1/(1 + [\mathit{discount\ rate}])\right)^{64}$

[b] 64 years ≈ 2 × [average age of mothers giving birth in 2014]. The average age of mothers giving birth in 2014 was 32.04 years (Statistics Korea, 2015a)

[c] South Korea's GDP in 2010 = 1,014,700 million US dollars (BOK, 2013).

Chapter 6

CONCLUSION

6.1 Conclusion

6.1.1 South Korea's climate and sustainable development measures, and the E4 framework

This study looked into the progression of South Korea's sustainability from 1998 to 2010. The reason why the year 1998 is the first year of the study period is the importance of the UNFCCC and the Kyoto Protocol on South Korea's sustainability policy development. The UNFCCC initiated the country's national interests in sustainability. Especially since signing the Kyoto Protocol in 1998, South Korea was forced to develop measures to deal with the global treaty. Over time, the Korean people and their government became aware that climate policies couldn't be separated from national sustainability policies.

During the study period, the South Korean government has promoted a series of climate and sustainable development policy instruments by implementing five comprehensive measure plans. "Have these plans been effective in addressing issues caused by or related to climate change and in promoting overall sustainability in South Korea?" To assess the effectiveness of the country's policy measures, this study adopted a conceptual framework of sustainability, which is called the 'E4' (economy, energy, environment, & equity) approach.

6.1.2 Energy Systems Theory and E4-Emergy database development

To assess the progression of E4 sustainability quantitatively, this study adopted H. T. Odum's Energy Systems Theory. The Energy Systems Theory provided a very useful environmental accounting method called emergy (energy memory). Compared to the conventional energy accounting counterparts, emergy accounting methods showed many advantages to evaluate South Korea's sustainability under the E4 framework. Especially, emergy accounting provided sufficient information about how energy use is related to the economy and the environment in the country and was strictly compliant with thermodynamic principles. One shortcoming of the previous studies using emergy accounting is the limited explanation of equity issues, which was addressed in this study by developing an additional emergy-equity database.

Although this study adopted existing transformities and Unit Emergy Values (UEVs) from the literature, many primary data were recalculated with a rigorous re-evaluation of renewable and non-renewable resource flows in South Korea over the 1998-2010 study period. Development of a time series E4 database conforming to the emergy accounting principle is another achievement of the study.

6.1.3 E4-Emergy evaluation

Results of the emergy evaluation were classified into each of the four 'E' sustainability categories. The indices and indicators synthesized from the results are compared with key well-known sustainability indicators that are produced from conventional energy accounting methods. In addition, the results of the E4-Emergy evaluation were compared with those of 9 countries that have comparable emergy studies.

Two merits can be found in this process. First, comparison of indices and indicators generated from emergy accounting and the conventional energy accounting showed that emergy accounting let us find hidden meanings from resource flows and gain new insights into many parts of the E4 framework. Those new explanations and insights could not have been easily obtained from the conventional energy accounting methods. Secondly, comparison of South Korea with 9 countries showed us how South Korea's E4 sustainability has changed not only in absolute terms but also relative to other countries. The overall message from the 10-country comparison was South Korea's failure in translating climate and sustainable development measures into real improvement of E4 sustainability.

6.1.4 Policy implications

The new explanations and insights gained from the E4-Emergy evaluation called for major policy changes in South Korea. The policy implications can be presented in two groups.

First, a policy suggestion from comparison of conventional energy accounting and emergy accounting is to institutionalize emergy accounting in South Korea. To reflect the flows and stocks of natural resources in its national accounts, South Korea can begin the preparatory work by collecting the necessary data to evaluate and refine unit emergy values (UEVs) of the resources. If the country can re-evaluate imported goods and services by emergy accounting, the country will have a strong data infrastructure to formulate robust policy options.

Second, policy implications from the E4-Emergy evaluation of South Korea found in each of the E4 sustainability elements. For economic sustainability, a culture of descent was recommended and, to rescue South Korea from growth oriented economic policy and excessive money supply, grassroots movements like local currencies were suggested as a beginning point of change. For energy sustainability, maximizing renewable energy was found to be an inevitable policy direction. Re-introduction of feed-in tariff and reforms in the current Renewable Portfolio Standard

(RPS) policies were suggested. For environmental sustainability, South Korea was required to smooth out the transition into scarcity or depletion of resources. Suggested policies were a comprehensive measurement of resource use at product, company, and industry levels, the promotion of the circular economy, and stronger diversification of economies. Lastly, for equity sustainability, two policy directions were recommended: to improve intragenerational equity and to secure intergenerational equity. To improve intragenerational equity, policies to mitigate energy poverty were mentioned. In addition, a minimum pension guarantee was found to be an option to ease the most prominent cause of inequity, old age poverty. As for intergenerational equity, significantly lower social discount rates for future development of domestic resources were found to be an imperative to ensure a higher probability of future generations' welfare.

6.2 Further Research

Although this study has garnered many methodological progresses in environmental accounting and new insights for E4 sustainability improvement, there are many shortcomings that need further research. In this section, two most urgent topics related to the shortcoming are briefly discussed.

6.2.1 Intragenerational equity analysis that includes non-residential and non-energy consumption of different income groups

Due to limitations in data availability, this study has evaluated only the residential energy consumption patterns of different income groups. Non-residential energy consumption like the energy consumption for transportation was not examined. The study couldn't address non-energy consumption of households such as food, appliances and tourism, either.

To fully evaluate the states of inequity between different income groups, those aspects of emergy use must be considered. If a comprehensive survey of household consumption in emergy terms is not practically possible, a first step would be indirectly estimating required values from monetary expenditure such as the Household Income and Expenditure Survey (Statistics Korea, 2012, 2015c).

6.2.2 A principle of adaptive governance resulting from E4-Emergy evaluation

The following discussion is not a direct result of this study's analysis. However, throughout the process of E4-Emergy evaluation, it became clear that a theoretical background for developing appropriate policies for South Korea's E4 sustainability is essential.

South Korea in the 21st century is much different from the newly independent country in 1950. In 2012, it became the world's 14th largest economy by nominal GDP, traded goods and services with more than 230 countries, and ranked 14th in the world (if Hong Kong is excluded) by the Human Development Index (KITA, 2015; UNDP, 2014; World Bank, 2014). Its technological and institutional progress keeps pace with that of the world's leading countries (FTSE, 2014; K-Developedia, 2015). South Korea is exactly a "complex, multivariable, nonlinear, cross-scale, and changing" system (Ostrom, 2007). Top-down approaches by the central government's blue-print plans would not work effectively in adaptive governance settings. Ludwig (2001) bluntly declared that external experts cannot 'manage' a society, because they lack local knowledge and genuine interest in the area.

In South Korea, policy development procedure is very unique. Government officials internally propose several policy instruments to achieve certain government objectives. Then the government branch initiates research projects to evaluate the appropriateness and relevance of the instruments (K. W. Chung, 2011). The evaluation projects are mostly conducted by government-funded research institutions. Even some projects carried out by external research groups closely cooperate with the government-affiliated research institutions. Research outcomes are reviewed by committees. Committee members are apparently composed of representatives of diverse social sectors, namely university professors, company executives, civil society workers. However, they are essentially appointed by government officials. Review results consequently conform to government policy agendas. Although nobody denies the superior capacity of high officials of the Korean government, the policy development procedure does not accommodate learning or cooperation. Adaptation or learning, if any, happens only after a large scale policy failure is detected by mass media or from the highest governmental levels.

To implement the E4 framework for a country like South Korea, a specific kind of governance is required. Dynamic and complex problems like sustainable energy policy development cannot be solved by a few experts in a short time (Leach, Scoones, & Stirling, 2010; Stirling, 2010). At the same time, policy development needs experts. Decision makers' indecision does not result from political opposition, but is due to their misunderstanding or negligence (Patt, 2009). While even the very low growth strategy for sustainability has self-conflicting biophysical problems, taking action and learning from the experiment must not be postponed (Sorman & Giampietro, 2013). Policymakers have to begin with the smallest changes, involving many small and big actors (Ostrom, 2009, 2012). Sustainability needs action rather than endless inaction just waiting for a legally binding regulation or strong political consensus (Lowitt, 2012).

In this complex context, adaptive governance[6] based on resilience theory is appropriate for policy development and implementation (Ansari, Gray, & Wijen, 2011; Folke, Hahn, Olsson, & Norberg, 2005). The theory of adaptive governance was developed with huge contributions from ecological studies.

First, concepts of adaptive cycles and pulsing oscillations lay a foundation for adaptive governance (Farrelly, Rijke, & Brown, 2012; Garver, 2011; L. Gunderson & Light, 2006; Pisano, 2012). With uncertainties, a unidirectional change towards a steady state or static equilibrium cannot be pursued. To solve this problem, ecologists devised new explanatory tools. The two most widely utilized tools are two-dimensional "pulsing oscillators" (Odum & Odum, 2001, 2006) or three-dimensional "adaptive cycles" involving resilience (Holling, 2001; Holling & Gunderson, 2002).

---

[6] Different aspects of adaptive governance give it various other names. First, because of its emphasis on experimentation and collective learning (learning-by-doing), it's also called reflexive governance (Voß & Bornemann, 2011). Second, to effectively react to the problems, adaptive governance calls for multiple stakeholders' involvement, interaction of science and politics, and administrative boundaries (Klinke & Renn, 2011; Sovacool, 2011). So it's also called networked or collaborative governance (Huppé, Creech, & Knoblauch, 2012; Stauffacher, Krütli, Flüeler, & Scholz, 2012). Third, because sustainability takes a very long time to promote and manage, adaptive governance is called transition management (Loorbach, 2010). Fourth, adaptive governance is very similar to polycentric governance. Bottom-up (Laborgne, 2011), multi-level, or polycentrism (Sovacool, 2011) policy negotiation is essential in adaptive governance. Even national-level policy makers must consider sub-national level governance to bring about effective implementation of environmental policies (Shobe & Burtraw, 2012). Local governments have shown more agile policy development for sustainability than national governments (Byrne, Hughes, Rickerson, & Kurdgelashvili, 2007). Distributed energy systems managed by local governments are more agile and resilient to vulnerabilities (O'Brien & Hope, 2010). Fifth, "risk management" approach is similar to adaptive governance. The approach addresses risks with larger impacts or damages first by implementing either mitigation or adaptation depending on the magnitude of each anticipated or experiencing risk (Kunreuther et al., 2013).

Second, a modified equilibrium theory of ecology is used in adaptive governance. Once adaptive governance is adopted by a society or a country, sustainability becomes a continuous open-ended process, rather than a closed equilibrium target (Frantzeskaki, Loorbach, & Meadowcroft, 2012).

Third, adaptive governance's acknowledgement of uncertainties in data and future changes in policy development (Ahern, 2011; Goldstein, 2012; Voß & Bornemann, 2011) comes from explorative systems approach, which is in opposition to the exploitative systems approach (Goldthau & Sovacool, 2012). With uncertainties embodied in future changes, policies and researches have to be prepared for the worst. However, governments don't have enough resources for every possible worst case event (Nordhaus, 2011). So they need an approach that is not fail-safe, but safe-to-fail (Ahern, 2011).

There is one last point to raise for more effective implementation of adaptive governance in South Korea. Data availability and accessibility must be significantly improved. Public data (generated or collected by governments and public institutions) and academic resources must be shared transparently. Two practical approaches can be noted in the following.

First, in South Korea, public data have been off limits to non-government sectors. The energy policy development process in South Korea has been called very secretive and even the government-led "governance" has been only nominal and without real cooperation between stakeholders (C.-W. Kang & Park, 2015). Especially sensitive data like nuclear safety are sacred for government officials and managed with levels of security clearance similar to national security matters (H. Kim, 2014; Yun, 2015), which has only led to industry-wide corruption scandals (Tanter, 2013).

As another example, emissions reduction targets for Korea's Intended Nationally Determined Contribution (INDC) that would be eventually submitted to the UNFCCC (Korean Government, 2015) were not disclosed to non-government members of the committee until the final emissions targets were announced by the government (J.-I. Kim et al., 2015). Even after certain targets were disclosed, the government incurred distrust or suspicion by prohibiting third-party scholars or civil society from replicating results of the government-funded research that became the basis of the government's decisions (Cin, 2008; KIEP, 2006).

Second, there is gap between research and practice for civil society practitioners such as environmental movement activists that has been pointed out by Tewksbury and Wagner (2014). In South Korea, for example, non-governmental organizations (NGOs) do not have much access to academic resources. Although some activists have access while they study for advanced degrees at universities, it is one thing for them to read scientific papers at school, while it is quite another to respond in a timely manner to each of numerous social-environmental issues with state-of-the-art theories, best practices drawn from all over the world, and quantitative data, much of which are exclusively available to subscribing institutions.

All in all, implementing this robust principle of adaptive governance will further promote South Korea's E4 sustainability along with E4-Emergy evaluation studies. How to apply this principle through the implementation of the suggested policies in this study must be addressed in a future study.

REFERENCES

Act. (2010). *Framework Act on Low Carbon, Green Growth*. (No. 9931). Seoul, Korea: The Korean Government.

Ahern, J. (2011). From fail-safe to safe-to-fail: Sustainability and resilience in the new urban world. *Landscape and Urban Planning, 100*(4), 341-343. doi:10.1016/j.landurbplan.2011.02.021

Ahn, S., Shim, S., Jang, J., Kim, S., Seo, K. R., Kim, S. Y., . . . Lee, Y. N. (2008). *A Study on General Guidelines for Pre-Feasibility Study*. Seoul, Korea: Korea Development Institute Retrieved from https://www.kdi.re.kr/report/report_class_etc.jsp?pub_no=11672.

Ansari, S., Gray, B., & Wijen, F. (2011). Fiddling while the ice melts? How organizational scholars can take a more active role in the climate change debate1. *Strategic Organization, 9*(1), 70-76. doi:10.1177/1476127010395525

Arrow, K. J., Cropper, M. L., Gollier, C., Groom, B., Heal, G. M., Newell, R. G., . . . Weitzman, M. L. (2014). Should Governments Use a Declining Discount Rate in Project Analysis? *Review of Environmental Economics and Policy, 8*(2), 145-163. doi:10.1093/reep/reu008

Ascione, M., Bargigli, S., Campanella, L., & Ulgiati, S. (2011). Exploring an Urban System's Dependence on the Environment as a Source and a Sink: The City of Rome (Italy) Across Space and Time Scales. *ChemSusChem, 4*(5), 613-627. doi:10.1002/cssc.201000214

Ascione, M., Campanella, L., Cherubini, F., & Ulgiati, S. (2009). Environmental driving forces of urban growth and development: An emergy-based assessment of the city of Rome, Italy. *Landscape and Urban Planning, 93*(3-4), 238-249. doi:10.1016/j.landurbplan.2009.07.011

Atkinson, A. B. (2015). *Inequality: What Can Be Done?* Cambridge, MA: Harvard University Press.

Ba, A. D. (2013). Asian financial crisis *Encyclopædia Britannica*.

Bacon, R., Bhattacharya, S., & Kojima, M. (2010). *Expenditure of Low-Income Households on Energy: Evidence from Africa and Asia*. Washington, DC: World Bank Retrieved from http://documents.worldbank.org/curated/en/2010/06/12390075/expenditure-low-income-households-energy-evidence-africa-asia.

Bakshi, B. R., Baral, A., & Hau, J. L. (2011). Accounting for Resource Use by Thermodynamics. In B. R. Bakshi, T. G. Gutowski, & D. P. Sekulić (Eds.), *Thermodynamics and the Destruction of Resources* (pp. 87-109). New York, NY: Cambridge University Press.

Bastianoni, S., Campbell, D. E., Susani, L., & Tiezzi, E. (2005). The solar transformity of oil and petroleum natural gas. *Ecological Modelling, 186*(2), 212-220. doi:10.1016/j.ecolmodel.2005.01.015

Baumgärtner, S., Klein, A., Thiel, D., & Winkler, K. (2015). Ramsey Discounting of Ecosystem Services. *Environmental and Resource Economics, 61*(2), 273-296. doi:10.1007/s10640-014-9792-x

Beddoe, R., Costanza, R., Farley, J., Garza, E., Kent, J., Kubiszewski, I., . . . Woodward, J. (2009). Overcoming systemic roadblocks to sustainability: The evolutionary redesign of worldviews, institutions, and technologies. *Proceedings of the National Academy of Sciences, 106*(8), 2483-2489. doi:10.1073/pnas.0812570106

Belk, R. (2014). You are what you can access: Sharing and collaborative consumption online. *Journal of Business Research, 67*(8), 1595-1600. doi:10.1016/j.jbusres.2013.10.001

Bellos, I., & Ferguson, M. (2015). Moving from a Product-Based Economy to a Service-Based Economy for a More Sustainable Future. Retrieved from http://mason.gmu.edu/~ibellos/bfchapter.pdf

BOE. (2013). *Energy Statistics Handbook 2012 (Second Edition)*. Taipei, Taiwan: Bureau of Energy (BOE), Ministry of Economic Affairs (MOEA) Retrieved from http://www.moeaboe.gov.tw/Download/opengovinfo/plan/all/files/EnergyStatisticalDataBook.pdf.

BOK. (2011). *Korean System of National Accounts: Concepts, Sources and Methods*. Seoul, Korea: The Bank of Korea.

BOK. (2013). Economic Statistics System (ECOS) Retrieved from http://ecos.bok.or.kr/. from The Bank of Korea http://ecos.bok.or.kr/

Bostan, I., Gheorghe, A., Dulgheru, V., Sobor, I., Bostan, V., & Sochirean, A. (2013). *Resilient Energy Systems - Renewables: Wind, Solar, Hydro*. Dordrecht, the Netherlands: Springer.

BP. (2014). *BP Statistical Review of World Energy 2014*. London, UK: BP p.l.c.

Brown, M. T. (2004). A picture is worth a thousand words: energy systems language and simulation. *Ecological Modelling, 178*(1-2), 83-100. doi:10.1016/j.ecolmodel.2003.12.008

Brown, M. T., & Buranakarn, V. (2003). Emergy indices and ratios for sustainable material cycles and recycle options. *Resources, Conservation and Recycling, 38*(1), 1-22. doi:10.1016/S0921-3449(02)00093-9

Brown, M. T., Cohen, M. J., & Sweeney, S. (2009). Predicting national sustainability: The convergence of energetic, economic and environmental realities. *Ecological Modelling, 220*(23), 3424-3438. doi:10.1016/j.ecolmodel.2009.08.023

Brown, M. T., & Herendeen, R. A. (1996). Embodied energy analysis and EMERGY analysis: a comparative view. *Ecological Economics, 19*(3), 219-235. doi:10.1016/S0921-8009(96)00046-8

Brown, M. T., & McClanahan, T. R. (1996). EMergy analysis perspectives of Thailand and Mekong River dam proposals. *Ecological Modelling, 91*(1-3), 105-130. doi:10.1016/0304-3800(95)00183-2

Brown, M. T., Raugei, M., & Ulgiati, S. (2012). On boundaries and ‘investments’ in Emergy Synthesis and LCA: A case study on thermal vs. photovoltaic electricity. *Ecological Indicators, 15*(1), 227-235. doi:10.1016/j.ecolind.2011.09.021

Brown, M. T., & Ulgiati, S. (1997). Emergy-based indices and ratios to evaluate sustainability: monitoring economies and technology toward environmentally sound innovation. *Ecological Engineering, 9*(1-2), 51-69. doi:10.1016/s0925-8574(97)00033-5

Brown, M. T., & Ulgiati, S. (2002). Emergy evaluations and environmental loading of electricity production systems. *Journal of Cleaner Production, 10*(4), 321-334. doi:10.1016/S0959-6526(01)00043-9

Brown, M. T., & Ulgiati, S. (2004). Emergy Analysis and Environmental Accounting. In C. J. Cleveland (Ed.), *Encyclopedia of Energy* (Vol. 2, pp. 329-354). Amsterdam, The Netherlands: Elsevier.

Brown, M. T., & Ulgiati, S. (2007). Emergy Accounting. In B. L. Capehart (Ed.), *Encyclopedia of Energy Engineering and Technology* (pp. 420-429). Boca Raton, FL: CRC Press.

Brown, M. T., & Ulgiati, S. (2010). Updated evaluation of exergy and emergy driving the geobiosphere: A review and refinement of the emergy baseline. *Ecological Modelling, 221*(20), 2501-2508. doi:10.1016/j.ecolmodel.2010.06.027

Buonocore, E., Franzese, P. P., & Ulgiati, S. (2012). Assessing the environmental performance and sustainability of bioenergy production in Sweden: A life cycle assessment perspective. *Energy, 37*(1), 69-78. doi:10.1016/j.energy.2011.07.032

Byrne, J., Hughes, K., Rickerson, W., & Kurdgelashvili, L. (2007). American policy conflict in the greenhouse: Divergent trends in federal, regional, state, and local green energy and climate change policy. *Energy Policy, 35*(9), 4555-4573. doi:10.1016/j.enpol.2007.02.028

Cai, Z. F., Zhang, L. X., Zhang, B., & Chen, Z. M. (2009). Emergy-based analysis of Beijing–Tianjin–Tangshan region in China. *Communications in Nonlinear Science and Numerical Simulation, 14*(12), 4319-4331. doi:10.1016/j.cnsns.2009.03.009

Campbell, D. E. (1998). Emergy Analysis of Human Carrying Capacity and Regional Sustainability: an Example Using the State of Maine. *Environmental Monitoring and Assessment, 51*(1-2), 531-569. doi:10.1023/A:1006043721115

Campbell, D. E. (2000). A Revised Solar Transformity for Tidal Energy Received by the Earth and Dissipated Globally: Implications for Emergy Analysis. In M. T. Brown (Ed.), *Emergy Synthesis: Theory and Applications of the Emergy Methodology* (pp. 255-263). Gainesville, FL: The Center for Environmental Policy.

Campbell, D. E. (2015, October 22). [Specific Emergies of VOC & CO].

Campbell, D. E., Brandt-Williams, S. L., & Cai, T. (2005). Current Technical Problems in Emergy Analysis. In M. T. Brown (Ed.), *Emergy Synthesis 3: Theory and Applications of the Emergy Methodology* (pp. 143-157). Gainesville, FL: The Center for Environmental Policy.

Campbell, D. E., Brandt-Williams, S. L., & Meisch, M. E. A. (2005). *Environmental Accounting Using Emergy: Evaluation of the State of West Virginia*. (EPA/600/R-05/006). Washington, DC: United States Environmental Protection Agency (EPA) Retrieved from http://www.epa.gov/nheerl/download_files/publications/wvevaluationposted.pdf.

Campbell, D. E., & Garmestani, A. S. (2012). An energy systems view of sustainability: Emergy evaluation of the San Luis Basin, Colorado. *Journal of Environmental Management, 95*(1), 72-97. doi:10.1016/j.jenvman.2011.07.028

Campbell, D. E., & Lu, H. (2009). The Emergy to Money Ratio of the United States from 1900 to 2007. In M. T. Brown (Ed.), *Emergy Synthesis 5: Theory and Applications of the Emergy Methodology* (pp. 413-448). Gainesville, FL: The Center for Environmental Policy.

Campbell, D. E., Lu, H., & Lin, B.-L. (2014). Emergy evaluations of the global biogeochemical cycles of six biologically active elements and two compounds. *Ecological Modelling, 271*, 32-51. doi:10.1016/j.ecolmodel.2013.01.013

Campbell, D. E., Lu, H., & Walker, H. A. (2014). Relationships among the Energy, Emergy and Money Flows of the United States from 1900 to 2011. *Frontiers in Energy Research, 2*, Article 41. doi:10.3389/fenrg.2014.00041

Campbell, D. E., & Ohrt, A. (2009). *Environmental Accounting Using Emergy: Evaluation of Minnesota*. (EPA/600/R-09/002). Washington, DC: United States Environmental Protection Agency (EPA) Retrieved from http://www.epa.gov/nheerl/download_files/publications/MNEmergyEvalfinal2009_1_16.pdf.

Campbell, E. T. (2012). *Valuing Forest Ecosystem Services in Maryland and Suggesting Fair Payment Using the Principles of Systems Ecology*. (Doctoral dissertation), University of Maryland, College Park, MD. Retrieved from http://drum.lib.umd.edu/handle/1903/13093

Center for Environmental Policy. (2009). *National Environmental Accounting Database*. Retrieved from: http://sahel.ees.ufl.edu/frame_database_resources_test.php?search_type=basic

Chen, G. Q. (2006). Scarcity of exergy and ecological evaluation based on embodied exergy. *Communications in Nonlinear Science and Numerical Simulation, 11*(4), 531-552. doi:10.1016/j.cnsns.2004.11.009

Chen, H., Chen, G. Q., & Ji, X. (2010). Cosmic emergy based ecological systems modelling. *Communications in Nonlinear Science and Numerical Simulation, 15*(9), 2672-2700. doi:10.1016/j.cnsns.2009.09.025

Choi, H. (2014, October 2). Stalled REC market calls for urgent policy reformation. *Electronic Times*. Retrieved from http://www.etnews.com/20141008000305

Choi, J.-W., Choe, C. S., & Kim, J. (2012). *Local Government and Public Administration in Korea*. Suwon, Korea: Local Government Officials Development Institute (LOGODI) Retrieved from http://www.prism.go.kr/homepage/researchCommon/downloadResearchAttachFile.do?work_key=001&file_type=CPR&seq_no=001&pdf_conv_yn=N&research_id=1311000-201200031.

Choi, J. Y., Jeon, S. W., Park, C. S., & Yoon, J. H. (2004). *National environmental capacity estimation model development and national environmental indicators establishment*. Gwacheon, Korea: Ministry of Environment.

Choulot, A., Denis, V., & Punys, P. (2012). Integration of Small Hydro Turbines into Existing Water Infrastructures. In H. Samadi-Boroujeni (Ed.), *Hydropower: Practice and Application*. Rijeka, Croatia: InTech.

Christ, K. L., & Burritt, R. L. (2014). Material flow cost accounting: a review and agenda for future research. *Journal of Cleaner Production*(In Press). doi:10.1016/j.jclepro.2014.09.005

Chung, K. W. (2011). *The Same Policy, Similar Procedure but Different Consequence: Analyzing Policy-Shaping Processes of Greenhouse Gas Emissions Trading Scheme in the EU and Korea.* (Master's thesis), Lunds Universitet, Lund, Sweden. Retrieved from http://www.lumes.lu.se/database/alumni/09.11/Thesis/Kyeong%20Wha_Chung_thesis_2011.pdf

Chung, Y.-K., & Hwang, K. (2006). *The Korean National Strategy for Sustainable Development: A Background Report*. Asan, Korea: Department of International Economics, Sunmoon University Retrieved from https://sustainabledevelopment.un.org/content/documents/1394backgroundReport.pdf.

CIA. (2012). Coastline. In CIA (Ed.), *The World Factbook*. Langley, VA: Central Intelligence Agency.

Cin, B. C. (2008). An Analysis of Macroeconomic Effects of the Korea-U.S. FTA in the CGE Model: A Critical Overview and Simulation Results. *The Review of Social & Economic Studies, 30*, 81-127.

Cohen, M. J., Brown, M. T., & Shepherd, K. D. (2006). Estimating the environmental costs of soil erosion at multiple scales in Kenya using emergy synthesis. *Agriculture, Ecosystems & Environment, 114*(2–4), 249-269. doi:10.1016/j.agee.2005.10.021

Cohen, M. J., Sweeney, S., King, D., Shepherd, G., & Brown, M. T. (2012). *Environmental Accounting of National Economic Systems: An Analysis of West African Dryland Countries within a Global Context*. Nairobi, Kenya: United Nations Environment Programme Retrieved from http://www.unep.org/dewa/Portals/67/pdf/EANE_Report_lowres.pdf.

Coscieme, L., Pulselli, F. M., Marchettini, N., Sutton, P. C., Anderson, S., & Sweeney, S. (2014). Emergy and ecosystem services: A national biogeographical assessment. *Ecosystem Services, 7*, 152-159. doi:10.1016/j.ecoser.2013.11.003

Costanza, R., Alperovitz, G., Daly, H., Farley, J., Franco, C., Jackson, T., . . . Victor, P. (2012). *Building a Sustainable and Desirable Economy-in-Society-in-Nature*. New York, NY: United Nations Division for Sustainable Development Retrieved from http://www.un.org/esa/dsd/dsd_sd21st/21_pdf/Building_a_Sustainable_and_Desirable_Economy-in-Society-in-Nature.pdf.

Daly, H. E. (2009). From a Failed Growth Economy to a Steady-State Economy. *ISEE Newsletter, 2009*(October), 7–11. Retrieved from http://isecoeco.org/pdf/Oct2009.pdf

Dempsey, N., Bramley, G., Power, S., & Brown, C. (2011). The social dimension of sustainable development: Defining urban social sustainability. *Sustainable Development, 19*(5), 289-300. doi:10.1002/sd.417

DG Environment. (2013). *Options for Resource Efficiency Indicators*. Brussels, Belgium: European Commission Retrieved from http://ec.europa.eu/environment/consultations/pdf/consultation_resource.pdf.

DGBAS. (2013). *Statistical Yearbook of the Republic of China 2012*. Taipei, Taiwan: Directorate-General of Budget, Accounting and Statistics (DGBAS) Retrieved from http://ebook.dgbas.gov.tw/public/Data/3117141132EDNZ45LR.pdf.

Dincer, I., & Rosen, M. A. (2007). *Exergy: Energy, Environment and Sustainable Development*. Oxford, UK: Elsevier.

Dittmer, K. (2015). 100 percent reserve banking: A critical review of green perspectives. *Ecological Economics, 109*, 9-16. doi:10.1016/j.ecolecon.2014.11.006

Dow, S., Johnsen, G., & Montagnoli, A. (2015). A Critique of Full Reserve Banking. *Sheffield Economic Research Paper Series (SERPS), 2015008*. Retrieved from https://uuu.shef.ac.uk/polopoly_fs/1.448817!/file/paper_2015008.pdf

Druckman, A., & Jackson, T. (2008). Household energy consumption in the UK: A highly geographically and socio-economically disaggregated model. *Energy Policy, 36*(8), 3177-3192. doi:10.1016/j.enpol.2008.03.021

Edmonds, T., Jarrett, T., & Woodhouse, J. (2010). *The credit crisis: a timeline*. (SN/BT/4991). London, UK: House of Commons Library Retrieved from http://www.parliament.uk/briefingpapers/commons/lib/research/briefings/snbt-04991.pdf.

EIA. (2012). *Residential Energy Consumption Survey (RECS)*. Washington, DC: U.S. Energy Information Administration Retrieved from http://www.eia.gov/consumption/residential/index.cfm.

EIA. (2015). *International Energy Statistics*. Washington, DC: U.S. Energy Information Administration Retrieved from http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm.

Elliston, B., MacGill, I., & Diesendorf, M. (2013). Least cost 100% renewable electricity scenarios in the Australian National Electricity Market. *Energy Policy, 59*, 270-282. doi:10.1016/j.enpol.2013.03.038

Fahd, S., Mellino, S., & Ulgiati, S. (2012). Energy cropping in marginal land: Viable option or fairy tale? In D. Pimentel (Ed.), *Global economic and environmental aspects of biofuels* (pp. 51-95). Boca Raton, FL: CRC Press.

Farrelly, M. A., Rijke, J., & Brown, R. R. (2012). *Exploring operational attributes of governance for change*. Paper presented at the 7th International Conference on Water Sensitive Urban Design, Melbourne, Australia. http://www.waterforliveability.org.au/wp-content/uploads/WSUD2012-Farrelly-et-al.pdf

Federal Reserve Bank of St. Louis. (2011). *The Financial Crisis: A Timeline of Events and Policy Actions*. St, Louis, MO: Federal Reserve Bank of St. Louis Retrieved from http://timeline.stlouisfed.org/pdf/CrisisTimeline.pdf.

Ferreyra, C., & Brown, M. T. (2007). Emergy perspectives on the Argentine economy during the 20th century: a tale of natural resources, exports and external debt. *International Journal of Environment and Sustainable Development, 6*(1), 17-35.

Folke, C., Hahn, T., Olsson, P., & Norberg, J. (2005). Adaptive Governance of Social-Ecological Systems. *Annual Review of Environment and Resources, 30*(1), 441-473. doi:10.1146/annurev.energy.30.050504.144511

Frantzeskaki, N., Avelino, F., & Loorbach, D. (2013). Outliers or Frontrunners? Exploring the (Self-) Governance of Community- Owned Sustainable Energy in Scotland and the Netherlands. In E. Michalena & J. M. Hills (Eds.), *Renewable Energy Governance: Complexities and Challenges* (pp. 101-116). London, UK: Springer.

Frantzeskaki, N., Loorbach, D., & Meadowcroft, J. (2012). Governing societal transitions to sustainability. *International Journal of Sustainable Development, 15*(1-2), 19-36. doi:10.1504/IJSD.2012.044032

FRED. (2015a). *Federal Reserve Economic Data*. St. Louis, MO: Federal Reserve Bank of St. Louis Retrieved from https://research.stlouisfed.org/fred2/.

FRED. (2015b). *Monetary Trends: Velocity, Gross Domestic Product, and M2*. St. Louis, MO: Federal Reserve Bank of St. Louis Retrieved from https://research.stlouisfed.org/datatrends/mt/page12.php.

FTSE. (2014). South Korea – Developed or Emerging? Retrieved from http://www.ftseangle.com/2014/02/is-south-korea-a-developed-market-or-an-emerging-market/

Garratt, J. R. (1977). Review of Drag Coefficients over Oceans and Continents. *Monthly Weather Review, 105*(7), 915-929. doi:10.1175/1520-0493(1977)105<0915:RODCOO>2.0.CO;2

Garver, G. (2011). *A Framework for Novel and Adaptive Governance Approaches Based on Planetary Boundaries*. Paper presented at the 2011 Colorado Conference on Earth System Governance: Crossing Boundaries and Building Bridges, Fort Collins, CO: Colorado State University. http://cc2011.earthsystemgovernance.org/pdf/2011Colora_0110.pdf

Gasparatos, A., El-Haram, M., & Horner, M. (2008). A critical review of reductionist approaches for assessing the progress towards sustainability. *Environmental Impact Assessment Review, 28*(4–5), 286-311. doi:10.1016/j.eiar.2007.09.002

Gasparatos, A., El-Haram, M., & Horner, M. (2009). Assessing the sustainability of the UK society using thermodynamic concepts: Part 1. *Renewable and Sustainable Energy Reviews, 13*(5), 1074-1081. doi:10.1016/j.rser.2008.03.004

Gasparatos, A., & Gadda, T. (2009). Environmental support, energy security and economic growth in Japan. *Energy Policy, 37*(10), 4038-4048. doi:10.1016/j.enpol.2009.05.011

Geng, Y., Sarkis, J., Ulgiati, S., & Zhang, P. (2013). Measuring China's Circular Economy. *Science, 339*(6127), 1526-1527. doi:10.1126/science.1227059

Giampietro, M., & Sorman, A. H. (2012). Are energy statistics useful for making energy scenarios? *Energy, 37*(1), 5-17. doi:10.1016/j.energy.2011.08.038

Giannetti, B. F., Almeida, C. M. V. B., & Bonilla, S. H. (2012). Can emergy sustainability index be improved? Complementary insights for extending the vision. *Ecological Modelling, 244*, 158-161. doi:10.1016/j.ecolmodel.2012.02.027

Giannetti, B. F., Barrella, F. A., & Almeida, C. M. V. B. (2006). A combined tool for environmental scientists and decision makers: ternary diagrams and emergy accounting. *Journal of Cleaner Production, 14*(2), 201-210. doi:10.1016/j.jclepro.2004.09.002

Gifford, R. (2011). The dragons of inaction: Psychological barriers that limit climate change mitigation and adaptation. *American Psychologist, 66*(4), 290-302. doi:10.1037/a0023566

Giljum, S., & Hinterberger, F. (2014). The Limits of Resource Use and Their Economic and Policy Implications. In M. Angrick, A. Burger, & H. Lehmann (Eds.), *Factor X: Policy, Strategies and Instruments for a Sustainable Resource Use* (pp. 3-17). Dordrecht, The Netherlands: Springer.

Gillenwater, M. (2008). Forgotten carbon: indirect CO_2 in greenhouse gas emission inventories. *Environmental Science & Policy, 11*(3), 195-203. doi:10.1016/j.envsci.2007.09.001

GIR. (2013). *Greenhouse gas emissions statistics*. Gwacheon, Korea: Greenhouse Gas Inventory & Research Center of Korea (GIR) Retrieved from http://j.mp/Korea_GHG_Statistics.

GIR. (2014). *2013 National Greenhouse Gas Inventory Report of Korea*. Seoul, Korea: Greenhouse Gas Inventory & Research Center of Korea (GIR).

Gnansounou, E. (2008). Assessing the energy vulnerability: Case of industrialised countries. *Energy Policy, 36*(10), 3734-3744. doi:10.1016/j.enpol.2008.07.004

Goldstein, B. E. (Ed.) (2012). *Collaborative Resilience: Moving Through Crisis to Opportunity*. Cambridge, MA: The MIT Press.

Goldthau, A., & Sovacool, B. K. (2012). The uniqueness of the energy security, justice, and governance problem. *Energy Policy, 41*, 232-240. doi:10.1016/j.enpol.2011.10.042

Goode, P. R., Qiu, J., Yurchyshyn, V., Hickey, J., Chu, M. C., Kolbe, E., . . . Koonin, S. E. (2001). Earthshine observations of the Earth's reflectance. *Geophysical Research Letters, 28*(9), 1671-1674. doi:10.1029/2000GL012580

Grönlund, E., Fröling, M., & Carlman, I. (2015). Donor values in emergy assessment of ecosystem services. *Ecological Modelling, 306*, 101–105. doi:10.1016/j.ecolmodel.2014.10.011

Gunderson, L., & Light, S. (2006). Adaptive management and adaptive governance in the everglades ecosystem. *Policy Sciences, 39*(4), 323-334. doi:10.1007/s11077-006-9027-2

Gunderson, L. H., & Holling, C. S. (2002). *Panarchy: Understanding Transformations in Human and Natural Systems*. Washington, DC: Island Press.

Gupta, E. (2008). Oil vulnerability index of oil-importing countries. *Energy Policy, 36*(3), 1195-1211. doi:10.1016/j.enpol.2007.11.011

Haden, A. C. (2003). *Emergy Evaluations of Denmark and Danish Agriculture: Assessing the Limits of Agricultural Systems to Power Society*. Retrieved from Uppsala, Sweden:

Hall, C. A. S., & Klitgaard, K. A. (2012). How to Do Biophysical Economics. In C. A. S. Hall & K. A. Klitgaard (Eds.), *Energy and the Wealth of Nations: Understanding the Biophysical Economy* (pp. 351-365). New York, NY: Springer.

Hau, J. L., & Bakshi, B. R. (2004). Expanding Exergy Analysis to Account for Ecosystem Products and Services. *Environmental Science & Technology, 38*(13), 3768-3777. doi:10.1021/es034513s

Havemann, J. (2013). The Great Recession of 2008-09: Year In Review 2009 *Encyclopædia Britannica*.

Häyhä, T., Franzese, P. P., & Ulgiati, S. (2011). Economic and environmental performance of electricity production in Finland: A multicriteria assessment framework. *Ecological Modelling, 223*(1), 81-90. doi:10.1016/j.ecolmodel.2011.10.013

Hills, J. (2012). *Getting the measure of fuel poverty: Final Report of the Fuel Poverty Review*. London, UK: Department of Energy and Climate Change (DECC) Retrieved from https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/48297/4662-getting-measure-fuel-pov-final-hills-rpt.pdf.

Holden, E., Linnerud, K., & Banister, D. (2014). Sustainable development: Our Common Future revisited. *Global Environmental Change, 26*, 130-139. doi:10.1016/j.gloenvcha.2014.04.006

Holling, C. S. (2001). Understanding the Complexity of Economic, Ecological, and Social Systems. *Ecosystems, 4*(5), 390-405. doi:10.1007/s10021-001-0101-5

Holling, C. S., & Gunderson, L. H. (2002). Resilience and Adaptive Cycles. In L. H. Gunderson & C. S. Holling (Eds.), *Panarchy: Understanding Transformations in Human and Natural Systems* (pp. 25-62). Washington, DC: Island Press.

Hoppe, T., Graf, A., Warbroek, B., Lammers, I., & Lepping, I. (2015). Local Governments Supporting Local Energy Initiatives: Lessons from the Best Practices of Saerbeck (Germany) and Lochem (The Netherlands). *Sustainability, 7*(2), 1900-1931. doi:10.3390/su7021900

Huang, S.-L., & Chen, C.-W. (2009). Urbanization and Socioeconomic Metabolism in Taipei: An Emergy Synthesis. *Journal of Industrial Ecology, 13*(1), 75-93. doi:10.1111/j.1530-9290.2008.00103.x

Huang, S.-L., Lee, C.-L., & Chen, C.-W. (2006). Socioeconomic metabolism in Taiwan: Emergy synthesis versus material flow analysis. *Resources, Conservation and Recycling, 48*(2), 166-196. doi:10.1016/j.resconrec.2006.01.005

Huppé, G. A., Creech, H., & Knoblauch, D. (2012). *The Frontiers of Networked Governance*. Retrieved from Winnipeg, Canada: http://www.iisd.org/pdf/2012/frontiers_networked_gov.pdf

Huybrechts, B., & Mertens, S. (2014). The Relevance of the Cooperative Model in the Field of Renewable Energy. *Annals of Public and Cooperative Economics, 85*(2), 193-212. doi:10.1111/apce.12038

ICCA. (2009). *A Study on Support Measures for the Energy Poor that Help Greenhouse Gas Mitigation*. Retrieved from Seoul, Korea:

ICCA. (2011). *A Study on Energy Consumption of Low Income Groups: Current State and Support Measures*. Retrieved from Seoul, Korea:

IEA. (2005). *Energy Statistics Manual*. Paris, France: IEA Publications Retrieved from http://www.iea.org/stats/docs/statistics_manual.pdf.

IEA. (2012a). *CO_2 Emissions from Fuel Combustion 2012: Highlights*. Paris, France: IEA Publications Retrieved from http://www.iea.org/media/statistics/CO2Highlights2012.XLS.

IEA. (2012b). *Energy Balances of Non-OECD Countries 2012*. Paris, France: IEA Publications.

IEA. (2012c). *Energy Balances of OECD Countries 2012*. Paris, France: IEA Publications.

IEA, & NEA. (2015). *Projected Costs of Generating Electricity – 2015 Edition*. Paris, France: OECD Publishing.

IPCC (Ed.) (2000). *Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge University Press.

IPCC (Ed.) (2001). *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge University Press.

Jacobson, A., Milman, A. D., & Kammen, D. M. (2005). Letting the (energy) Gini out of the bottle: Lorenz curves of cumulative electricity consumption and Gini coefficients as metrics of energy distribution and equity. *Energy Policy, 33*(14), 1825-1832. doi:10.1016/j.enpol.2004.02.017

Jamasb, T., & Meier, H. (2010). Household Energy Expenditure and Income Groups: Evidence from Great Britain. *EPRG Working Paper, 1003*. Retrieved from http://www.eprg.group.cam.ac.uk/wp-content/uploads/2010/02/JamasbMeierCombined-EPRG10031.pdf

Jin, S. H., Park, E. C., & Hwang, I. C. (2009). *Research and Analysis on the Actual Condition of Energy Consumption in Low-income Households*. Retrieved from Seoul, Korea:

Johansson, T. B. (2005). The Imperatives of Energy for Sustainable Development. In A. J. Bradbrook, R. Lyster, R. L. Ottinger, & W. Xi (Eds.), *The Law of Energy for Sustainable Development* (pp. 46-52). Cambridge, UK: Cambridge University Press.

Jørgensen, S. E. (2012). *Introduction to Systems Ecology*. Boca Raton, FL: CRC Press.

K-Developedia. (2015). *Development Overview: Overview of Korea's development experience*. Sejong, Korea: KDI School of Public Policy and Management Retrieved from https://www.kdevelopedia.org/Development-Overview.do.

Kang, C.-W., & Park, M.-S. (2015, July 20-22). Let's change the paradigm of energy policy. *The Hankook-ilbo*.

Kang, D., & Nam, J.-H. (2003). *Value assessment and policy implications of marine environment and resources using emergy concepts*. Seoul, Korea: Korea Maritime Institute.

Kaunda, C. S., Kimambo, C. Z., & Nielsen, T. K. (2012). Hydropower in the Context of Sustainable Energy Supply: A Review of Technologies and Challenges. *ISRN Renewable Energy, 2012*, 15. doi:10.5402/2012/730631

KCS. (2012a). *Actual exports and imports by commodity*. Daejeon, Korea: Korea Customs Service Retrieved from http://www.customs.go.kr/kcsweb/user.tdf?a=user.newTradestatistics.NewTradestatisticsApp&c=1003.

KCS. (2012b). *Summary of exports and imports*. Daejeon, Korea: Korea Customs Service Retrieved from http://www.customs.go.kr/kcsweb/user.tdf?a=user.newTradestatistics.NewTradestatisticsApp&c=1001.

KEEI. (2000). *Energy Consumption Survey 1999*. Gwacheon, Korea: Ministry of Commerce, Industry and Energy.

KEEI. (2003). *Energy Consumption Survey 2002*. Gwacheon, Korea: Ministry of Commerce, Industry and Energy.

KEEI. (2006). *Energy Consumption Survey 2005*. Gwacheon, Korea: Ministry of Commerce, Industry and Energy.

KEEI. (2009). *Energy Consumption Survey 2008*. Gwacheon, Korea: Ministry of Knowledge Economy.

KEEI. (2011). *Yearbook of Energy Statistics 2011*. Uiwang, Korea: Korea Energy Economics Institute.

KEEI. (2012a). *Energy Consumption Survey 2011*. Gwacheon, Korea: Ministry of Knowledge Economy.

KEEI. (2012b). *Yearbook of Energy Statistics 2012*. Uiwang, Korea: Korea Energy Economics Institute.

KEEI. (2015). *Korea Energy Statistics Information System (KESIS)*. Ulsan, Korea: Korea Energy Economics Institute Retrieved from http://www.kesis.net/.

KEMCO. (2008). *New & Renewable Energy Statistics 2007*. Yongin, Korea: Korea Energy Management Corporation (KEMCO).

KEMCO. (2011). *New & Renewable Energy Statistics 2010*. Yongin, Korea: Korea Energy Management Corporation (KEMCO).

KHOA. (2012). *Territorial Waters of the Republic of Korea: Based on the National Basic Survey of the Sea*. Incheon, Korea: Korea Hydrographic and Oceanographic Administration (KHOA) Retrieved from http://www.khoa.go.kr/tempdir/korea_territory.pdf.

KIEP. (2006). Explanation on the assertion of concealment or manipulation of the analysis data from the Study on the Economic Effects of Korea-U.S. FTA [Press release]. Retrieved from http://www.kiep.go.kr/skin.jsp?grp=news&bid=ResBodo&mode=view&num=126268

KIGAM. (2012). *Mineral Demand and Supply 2011*. Gwacheon, Korea: Ministry of Knowledge Economy.

Kim, B.-G., Lee, G.-J., & Lee, S.-J. (2005). *Environmental capacity and urban development capacity assessment of Jeollabuk-do*. Jeonju, Korea: Jeonbuk Development Institute.

Kim, C. H. (2009). *Management of High Level Nuclear Wastes*. Seoul, Korea: Korean Academy of Science and Technology (KAST).

Kim, H. (2014). Reconstructing the public in old and new governance: A Korean case of nuclear energy policy. *Public Understanding of Science, 23*(3), 268-282. doi:10.1177/0963662514524087

Kim, H. C., & Lee, Y. (2007). Heat flow in the Republic of Korea. *Journal of Geophysical Research: Solid Earth, 112*(B5), B05413. doi:10.1029/2006JB004266

Kim, J.-H., & Lee, E.-J. (2013). A Study on the Present State of Duty Performance According to the RPS System and Improvement Plan. *Journal of the Korean Solar Energy Society, 33*(6), 98-104. doi:10.7836/kses.2013.33.6.098

Kim, J.-I., Park, Y.-S., Seok, K.-H., Song, S., Ahn, B. O., Yang, W., . . . Ho, H. J. (2015). Our stance on the announcement of the government's greenhouse gas emissions reduction scenarios: A statement of the civil society appointees of the Private and Public Joint Review Committee on the Post-2020 Long-Term Greenhouse Gas Emissions Reduction Targets [Press release]. Retrieved from http://kfem.or.kr/?p=151330

Kim, S., & Yang, D. Y. (2012). Are Capital Controls Effective? The Case of the Republic of Korea. *Asian Development Review, 29*(2), 96-133. Retrieved from http://hdl.handle.net/11540/1637

KITA. (2015). *Numbers of traded items and trade partner countries*. Seoul, Korea: Korea International Trade Association (KITA) Retrieved from http://stat.kita.net/stat/world/major/KoreaStats04.screen.

Klinke, A., & Renn, O. (2011). Adaptive and integrative governance on risk and uncertainty. *Journal of Risk Research, 15*(3), 273-292. doi:10.1080/13669877.2011.636838

KMA. (2011). Monthly average temperature (1981-2010). Retrieved from http://www.kma.go.kr/weather/climate/average_30years.jsp

KMA. (2012a). *Annual Climatological Reports*. Seoul, Korea: Korea Meteorological Administration (KMA) Retrieved from http://www.kma.go.kr/weather/observation/data_monthly.jsp.

KMA. (2012b). *Monthly Reports of Marine Data (January to December)*. Seoul, Korea: Korea Meteorological Administration Retrieved from http://www.kma.go.kr/weather/observation/data_sea.jsp.

KMA. (2012c). *Precipitation trends*. Daejeon, Korea: Statistics Korea Retrieved from http://www.index.go.kr/egams/stts/jsp/potal/stts/PO_STTS_IdxSearch.jsp?idx_cd=1401.

KMA. (2012d). *Time-series of solar radiation data*. Seoul, Korea: Korea Meteorological Administration (KMA) Retrieved from http://www.kma.go.kr/weather/climate/solar_energy02.jsp.

KMA. (2013). *Monthly Reports of Marine Data (January to December)*. Seoul, Korea: Korea Meteorological Administration Retrieved from http://www.kma.go.kr/weather/observation/data_sea.jsp.

Ko, J.-Y., Hall, C. S., & López Lemus, L. (1998). Resource Use Rates and Efficiency as Indicators of Regional Sustainability: an Examination of Five Countries. *Environmental Monitoring and Assessment, 51*(1-2), 571-593. doi:10.1023/A:1006095822024

Korean Government. (2015). *Intended Nationally Determined Contribution*. Bonn, Germany: UNFCCC Secretariat Retrieved from http://www4.unfccc.int/submissions/INDC/Published%20Documents/Republic%20of%20Korea/1/INDC%20Submission%20by%20the%20Republic%20of%20Korea%20on%20June%2030.pdf.

KPX. (2015). *Electric Power Statistics Information System (EPSIS)*. Naju, Korea: Korea Power Exchange (KPX) Retrieved from https://epsis.kpx.or.kr/.

Kunreuther, H., Heal, G., Allen, M., Edenhofer, O., Field, C. B., & Yohe, G. (2013). Risk management and climate change. *Nature Climate Change, 3*(5), 447-450. doi:10.1038/nclimate1740

Kunze, C., & Becker, S. (2015). Collective ownership in renewable energy and opportunities for sustainable degrowth. *Sustainability Science, 10*(3), 425-437. doi:10.1007/s11625-015-0301-0

Kwon, S. M., Kim, S. Y., & Shin, G. J. (2014). *A Study on the Policy Improvement for Facilitation of Citizen-Participatory Renewable Energy Deployment*. Seoul, Korea: Office of Jenam Kim, National Assembly.

Laborgne, P. (2011). Energy Sustainability: The Role of Small Local Communities. In M. Järvelä & S. Juhola (Eds.), *Energy, Policy, and the Environment: Modeling Sustainable Development for the North* (Vol. 6, pp. 193-214). New York, NY: Springer.

Laitner, J. A. (2013). *Linking Energy Efficiency to Economic Productivity: Recommendations for Improving the Robustness of the U.S. Economy*. Retrieved from Washington, DC:

Lal, R. (2003). Soil erosion and the global carbon budget. *Environment International, 29*(4), 437-450. doi:10.1016/S0160-4120(02)00192-7

Latouche, S. (2009). *Farewell to Growth* (D. Macey, Trans.). Cambridge, UK: Polity Press.

Leach, M., Scoones, I., & Stirling, A. (2010). *Dynamic Sustainabilities: Technology, Environment, Social Justice*. London, UK: Earthscan.

Lee, C.-W., & Oh, Y. S. (1999). *Environmental Capacity Assessment of Seoul (I)*. Seoul, Korea: Seoul Development Institute.

Lee, H.-D. (2000). The Current State and Value of South Korea's Marine Ecological Resources. *Oceans and Fisheries Monthly, 195*, 52-62.

Lee, H. J., Park, S. K., Park, K.-S., Han, C., & Jun, J. (2013). *A Study on the Introduction of Energy Vouchers*. Seoul, Korea: Korea Institute for Health and Social Affairs (KIHASA) Retrieved from https://www.kihasa.re.kr/html/jsp/publication/policy/view.jsp?bid=12&ano=1586.

Lee, S.-D. (2013, March 12). Korean residential building area per household increases 31.3 m^2 over 30 years. *Maeil Business Newspaper*. Retrieved from http://vip.mk.co.kr/newSt/news/news_view.php?p_page=&sCode=21&t_uid=20&c_uid=973007

Lee, S. M., & Odum, H. T. (1994). Emergy Analysis Overview of Korea. *Journal of the Korean Environmental Sciences Society, 3*(2), 165-175.

Lee, T., Lee, T., & Lee, Y. (2014). An experiment for urban energy autonomy in Seoul: The One 'Less' Nuclear Power Plant policy. *Energy Policy, 74*, 311-318. doi:10.1016/j.enpol.2014.08.023

Lee, W.-S., Jung, S.-G., & You, J.-H. (2005). Evaluation of Emergy for Sustainable Development of Daegu. *Journal of Korea Planners Association, 41*(3), 137-150.

Lei, K., & Zhou, S. (2012). Per capita resource consumption and resource carrying capacity: A comparison of the sustainability of 17 mainstream countries. *Energy Policy*. doi:10.1016/j.enpol.2011.12.030

Liu, G., Yang, Z., Chen, B., & Ulgiati, S. (2009). Emergy-based urban health evaluation and development pattern analysis. *Ecological Modelling, 220*(18), 2291-2301. doi:10.1016/j.ecolmodel.2009.05.019

Liu, G., Yang, Z., Chen, B., & Ulgiati, S. (2011). Monitoring trends of urban development and environmental impact of Beijing, 1999–2006. *Science of The Total Environment, 409*(18), 3295-3308. doi:10.1016/j.scitotenv.2011.05.045

Liu, G., Yang, Z., Chen, B., & Zhang, L. (2011). Analysis of Resource and Emission Impacts: An Emergy-Based Multiple Spatial Scale Framework for Urban Ecological and Economic Evaluation. *Entropy, 13*(3), 720-743. doi:10.3390/e13030720

Loiseau, E., Junqua, G., Roux, P., & Bellon-Maurel, V. (2012). Environmental assessment of a territory: An overview of existing tools and methods. *Journal of Environmental Management, 112*, 213-225. doi:10.1016/j.jenvman.2012.07.024

Lomas, P. L., Álvarez, S., Rodríguez, M., & Montes, C. (2008). Environmental accounting as a management tool in the Mediterranean context: The Spanish economy during the last 20 years. *Journal of Environmental Management, 88*(2), 326-347. doi:10.1016/j.jenvman.2007.03.009

Loorbach, D. (2010). Transition Management for Sustainable Development: A Prescriptive, Complexity-Based Governance Framework. *Governance, 23*(1), 161-183. doi:10.1111/j.1468-0491.2009.01471.x

Lou, B., & Ulgiati, S. (2013). Identifying the environmental support and constraints to the Chinese economic growth—An application of the Emergy Accounting method. *Energy Policy, 55*, 217-233. doi:10.1016/j.enpol.2012.12.009

Lowitt, E. (2012, August 9). To solve climate change, let's move beyond climate change. *The Guardian*. Retrieved from http://www.guardian.co.uk/sustainable-business/blog/solve-climate-change-move-beyond

Lu, H., Ye, Z., Zhao, X.-F., & Peng, S.-L. (2003). A new emergy index for urban sustainable development. *Acta Ecologica Sinica, 23*(7), 1363-1368. Retrieved from http://www.cern.ac.cn/manage/ewebeditor/uploadfile/200592791044721.pdf

Ludwig, D. (2001). The Era of Management Is Over. *Ecosystems, 4*(8), 758-764. doi:10.1007/s10021-001-0044-x

Marchettini, N., Ridolfi, R., & Rustici, M. (2007). An environmental analysis for comparing waste management options and strategies. *Waste Management, 27*(4), 562-571. doi:10.1016/j.wasman.2006.04.007

Marcu, A., Egenhofer, C., Roth, S., & Stoefs, W. (2013) Carbon Leakage: An Overview. *Vol. 79. CEPS Special Report*. Brussels, Belgium: Centre for European Policy Studies (CEPS).

Meen, G. (2009). Modelling Local Spatial Poverty Traps in England. *Housing Studies, 24*(1), 127-147. doi:10.1080/02673030802547413

Meier, H., Jamasb, T., & Orea, L. (2013). Necessity or Luxury Good? Household Energy Spending and Income in Britain 1991-2007. *The Energy Journal, 34*(4), 109-128. doi:10.5547/01956574.34.4.6

Michel, A., & Hudon, M. (2015). Community currencies and sustainable development: A systematic review. *Ecological Economics, 116*, 160-171. doi:10.1016/j.ecolecon.2015.04.023

Millennium Ecosystem Assessment. (2005). *Ecosystems and Human Well-being: Synthesis*. Washington, DC: Island Press.

MKE, & KHNP. (2008). *Nuclear Power Note 2008*. Gwachoen, Korea: Ministry of Knowledge Economy.

MLTM. (2011). The 4th Long-Term Comprehensive Water Resources Plan (2011-2020): The 2nd Revision. Gwacheon, Korea: Ministry of Land, Transport and Maritime Affairs (MLTM).

MLTM. (2012). *National land status*. Daejeon, Korea: Statistics Korea Retrieved from http://www.index.go.kr/egams/stts/jsp/potal/stts/PO_STTS_IdxMain.jsp?idx_cd=2728.

MOE. (2013). *Environmental Statistics Yearbook 2013*. Sejong, Korea: Ministry of Environment.

MOE. (2014a). *Air Pollutant Emissions Trends*. Sejong, Korea: Ministry of Environment Retrieved from http://stat.me.go.kr/nesis/mesp/stat/branch/branchStat.do?task=I&leftMenu=stat&menu_id=106H_01_002.

MOE. (2014b). Water Information System. Retrieved from http://water.nier.go.kr/

MOE, & NIER. (2012). *Sectoral Climate Change Vulnerability Maps in Assistance for Local Government Adaptation Implementation Planning: Water Management, Ocean/Fisheries (Aquaculture), and Disaster (Infrastructure)*. Gwacheon, Korea: Ministry of Environment (MOE) & National Institute of Environmental Research (NIER).

MOF. (2013). *Oceans and Fisheries Administration by the Numbers*. Sejong-si, Korea: Ministry of Oceans and Fisheries Retrieved from http://www.korea.kr/common/download.do?fileId=183416099&tblKey=GMN.

MOGAHA. (2014). *Analysis of Settled Revenue of General Account (Overview)*. Seoul, Korea: Ministry of Government Administration and Home Affairs (MOGAHA) Retrieved from http://lofin.mogaha.go.kr/lofin_stat/settle/jejung/BudgetList.jsp?kind=settle.

MOGAHA. (2015). *Financial Independence of Local Governments*. Daejeon, Korea: Statistics Korea Retrieved from http://kosis.kr/statHtml/statHtml.do?orgId=101&tblId=DT_1YL7901&conn_path=I2.

Morandi, F., Campbell, D. E., & Bastianoni, S. (2014). Set theory applied to uniquely define the inputs to territorial systems in emergy analyses. *Ecological Modelling, 271*, 149-157. doi:10.1016/j.ecolmodel.2013.01.005

Mori, K., & Christodoulou, A. (2012). Review of sustainability indices and indicators: Towards a new City Sustainability Index (CSI). *Environmental Impact Assessment Review, 32*(1), 94-106. doi:10.1016/j.eiar.2011.06.001

Moss, J., McMann, M., Rae, J., Zipprich, A., Macer, D. R. J., Nyambati, A. R., . . . Wolbring, G. (2012). *Energy Equity and Environmental Security*. Bangkok, Thailand: UNESCO Bangkok Retrieved from http://www.unescobkk.org/fileadmin/user_upload/shs/Energyethics/EnergyEquityECCAPWG7proof.pdf.

Murphy, K. (2012). The social pillar of sustainable development: a literature review and framework for policy analysis. *Sustainability: Science, Practice, & Policy, 8*(1), 15-29.

Nam, J.-H., & Lee, Y. J. (2010). *An Innovative Management System for Public-owned Water to Protect Public Interests*. Seoul, Korea: Korea Maritime Institute.

NEA. (2012). *Uranium 2011: Resources, Production and Demand*. Paris, France: OECD/NEA Publishing Retrieved from http://dx.doi.org/10.1787/uranium-2011-en.

Neumayer, E. (2010). *Weak versus Strong Sustainability: Exploring the Limits of Two Opposing Paradigms* (3rd ed.). Cheltenham, UK: Edward Elgar.

NGII. (2010). *The Geography of Korea*. Suwon, Korea: National Geographic Information Institute (NGII) Retrieved from http://www.land.go.kr/document/info/The_Geography_of_Korea.pdf.

Noland, M. (2012). Korea's Growth Performance: Past and Future. *Asian Economic Policy Review, 7*(1), 20-42. doi:10.1111/j.1748-3131.2012.01212.x

Nordhaus, W. D. (2011). The Economics of Tail Events with an Application to Climate Change. *Review of Environmental Economics and Policy, 5*(2), 240-257. doi:10.1093/reep/rer004

Nurse, K. (2006). Culture as the fourth pillar of sustainable development. *Culture*(June), 32-48.

O'Brien, G., & Hope, A. (2010). Localism and energy: Negotiating approaches to embedding resilience in energy systems. *Energy Policy, 38*(12), 7550-7558. doi:10.1016/j.enpol.2010.03.033

O'Connor, M. (2006). The "Four Spheres" framework for sustainability. *Ecological Complexity, 3*(4), 285-292. doi:10.1016/j.ecocom.2007.02.002

O'Mahony, M., & Timmer, M. P. (2009). Output, Input and Productivity Measures at the Industry Level: The EU KLEMS Database. *The Economic Journal, 119*(538), F374-F403. doi:10.1111/j.1468-0297.2009.02280.x

Odum, H. T. (1967). Energetics of World Food Production. In Panel on the World Food Supply (Ed.), *The World Food Problem: A Report of the President's Science Advisory Committee - Volume III - Report of the Panel on the World Food Supply* (pp. 55-94). Washington, DC: The White House.

Odum, H. T. (1971). *Environment, Power, and Society*. New York, NY: John Wiley & Sons.

Odum, H. T. (1983). *Systems Ecology: An Introduction*. New York, NY: John Wiley & Sons.

Odum, H. T. (1994). *Ecological and General Systems: An Introduction to Systems Ecology* (Revised ed.). Niwot, CO: University Press of Colorado.

Odum, H. T. (1996). *Environmental Accounting: Emergy and Environmental Decision Making*. New York, NY: John Wiley & Sons.

Odum, H. T. (2007). *Environment, Power, and Society for the Twenty-First Century: The Hierarchy of Energy*. New York, NY: Columbia University Press.

Odum, H. T., & Odum, E. C. (2000). *Modeling for All Scales: An Introduction to System Simulation*. San Diego, CA: Academic Press.

Odum, H. T., & Odum, E. C. (2001). *A Prosperous Way Down: Principles and Policies*. Boulder, CO: University Press of Colorado.

Odum, H. T., & Odum, E. C. (2006). The prosperous way down. *Energy, 31*(1), 21-32. doi:10.1016/j.energy.2004.05.012

Odum, H. T., Odum, E. C., & Brown, M. T. (1997). *Environment and Society in Florida*. Boca Raton, FL: CRC Press.

OECD. (2012). *Factbook Country Statistical Profiles - 2013 edition*. Paris, France: OECD.Stat Retrieved from http://stats.oecd.org/Index.aspx?DataSetCode=CSP2012.

OECD. (2013). *Pensions at a Glance 2013: OECD and G20 Indicators*. Paris, France: OECD Publishing.

OECD. (2015a). Environment Database - Material resources   Retrieved from http://stats.oecd.org/Index.aspx?DataSetCode=MATERIAL_RESOURCES. Retrieved March 9, 2015, from OECD.Stat http://stats.oecd.org/Index.aspx?DataSetCode=MATERIAL_RESOURCES

OECD. (2015b). *Social Expenditure - Aggregated data*. Paris, France: OECD.Stat Retrieved from http://stats.oecd.org/Index.aspx?datasetcode=SOCX_AGG.

Oliveira, C., Martins, C., Gonçalves, J., & Veiga, F. (2013). Solar Emergy Evaluation of the Portuguese Economy. In M. T. Brown (Ed.), *Emergy Synthesis 7: Theory and Applications of the Emergy Methodology* (pp. 437-451). Gainesville, FL: The Center for Environmental Policy.

Osberg, L. (2014). *Can Increasing Inequality Be a Steady State?* Retrieved from Paris, France:

Ostrom, E. (2007). A diagnostic approach for going beyond panaceas. *Proceedings of the National Academy of Sciences, 104*(39), 15181-15187. doi:10.1073/pnas.0702288104

Ostrom, E. (2009). A Polycentric Approach for Coping with Climate Change. *Policy Research Working Paper,* (WPS5095). Retrieved from The World Bank website: http://www-wds.worldbank.org/external/default/WDSContentServer/WDSP/IB/2009/10/26/000158349_20091026142624/Rendered/PDF/WPS5095.pdf Retrieved from http://www-wds.worldbank.org/external/default/WDSContentServer/WDSP/IB/2009/10/26/000158349_20091026142624/Rendered/PDF/WPS5095.pdf

Ostrom, E. (2012). Nested externalities and polycentric institutions: must we wait for global solutions to climate change before taking actions at other scales? *Economic Theory, 49*(2), 353-369. doi:10.1007/s00199-010-0558-6

Paoli, C., Vassallo, P., & Fabiano, M. (2008). Solar power: An approach to transformity evaluation. *Ecological Engineering, 34*(3), 191-206. doi:10.1016/j.ecoleng.2008.08.005

Papathanasopoulou, E., & Jackson, T. (2009). Measuring fossil resource inequality—A case study for the UK between 1968 and 2000. *Ecological Economics, 68*(4), 1213-1225. doi:10.1016/j.ecolecon.2008.08.014

Park, S., Oh, C., Jeon, S., Jung, H., & Choi, C. (2011). Soil erosion risk in Korean watersheds, assessed using the revised universal soil loss equation. *Journal of Hydrology, 399*(3-4), 263-273. doi:10.1016/j.jhydrol.2011.01.004

Patt, A. (2009). Communicating uncertainty to policy makers. In P. C. Baveye, M. Laba, & J. Mysiak (Eds.), *Uncertainties in Environmental Modelling and Consequences for Policy Making* (pp. 231-251). Dordrecht, The Netherlands: Springer.

PCGG. (2009). *Five-Year Plan for Low Carbon, Green Growth (2009-2013)*. Seoul, Korea: Presidential Committee on Green Growth.

PCSD. (2006). *National Strategy for Sustainable Development (2006-2010)*. Seoul, Korea: Presidential Commission on Sustainable Development.

PECOS. (2014). *Handbook for Spent Nuclear Fuel*. Seoul, Korea: Public Engagement Commission on Spent Nuclear Fuel Management (PECOS).

Pereira, L., & Ortega, E. (2013). Assessment of Services in Emergy Accounting of Nations In M. T. Brown (Ed.), *Emergy Synthesis 7: Theory and Applications of the Emergy Methodology* (pp. 453-470). Gainesville, FL: The Center for Environmental Policy.

Piketty, T. (2014). *Capital in the Twenty-First Century* (A. Goldhammer, Trans.). Cambridge, MA: The Belknap Press.

Pisano, U. (2012). *Resilience and Sustainable Development: Theory of resilience, systems thinking and adaptive governance*. Retrieved from Vienna, Austria: http://www.sd-network.eu/quarterly%20reports/report%20files/pdf/2012-September-Resilience_and_Sustainable_Development.pdf

PMO. (1999). *Comprehensive Measures on Climate Change*. Seoul, Korea: Prime Minister's Office.

PMO. (2001). *The 2nd Comprehensive Measures on Climate Change*. Seoul, Korea: Prime Minister's Office.

PMO. (2004). *The 3rd Comprehensive Measures on Climate Change*. Seoul, Korea: Prime Minister's Office.

PMO. (2007). *The 4th Comprehensive Measures on Climate Change*. Seoul, Korea: Prime Minister's Office.

PMO. (2008). *Comprehensive Basic Plan for Climate Change*. Seoul, Korea: Prime Minister's Office.

Poelhekke, S., & van der Ploeg, F. (2015). Green Havens and Pollution Havens. *The World Economy, 38*(7), 1159–1178. doi:10.1111/twec.12219

Pretty, J. (2003). Social Capital and the Collective Management of Resources. *Science, 302*(5652), 1912-1914. doi:10.1126/science.1090847

Pulselli, R. M. (2010). Integrating emergy evaluation and geographic information systems for monitoring resource use in the Abruzzo region (Italy). *Journal of Environmental Management, 91*(11), 2349-2357. doi:10.1016/j.jenvman.2010.06.021

Pyo, H. K., Chun, H., & Rhee, K. (2012). *Korea Industrial Productivity Database 2012*. Seoul, Korea: Korea Productivity Center (KPC) Retrieved from http://www.kpc.or.kr/eng/state/2012_kip.asp.

Raugei, M., Rugani, B., Benetto, E., & Ingwersen, W. W. (2014). Integrating emergy into LCA: Potential added value and lingering obstacles. *Ecological Modelling, 271*, 4-9. doi:10.1016/j.ecolmodel.2012.11.025

Republic of Korea. (1987). *Constitution of the Republic of Korea*. Republic of Korea Retrieved from http://korea.assembly.go.kr/res/low_01_read.jsp?boardid=1000000035.

Robert, C., & Zeckhauser, R. (2011). The methodology of normative policy analysis. *Journal of Policy Analysis and Management, 30*(3), 613-643. doi:10.1002/pam.20578

Robertson, P. E., & Robitaille, M.-C. (2014). *The Gravity of Resources and the Tyranny of Distance*. UWA (University of Western Australia) Economics Discussion Paper. Retrieved from http://www.business.uwa.edu.au/__data/assets/pdf_file/0006/2711634/15.01-Robertson,-E.-and-Robitaille,-M.-THE-GRAVITY-OF-RESOURCES-AND-THE-TYRANNY-OF-DISTANCE.pdf

Rugani, B., Huijbregts, M. A. J., Mutel, C., Bastianoni, S., & Hellweg, S. (2011). Solar Energy Demand (SED) of Commodity Life Cycles. *Environmental Science & Technology, 45*(12), 5426-5433. doi:10.1021/es103537f

Ruggiero, S., Onkila, T., & Kuittinen, V. (2014). Realizing the social acceptance of community renewable energy: A process-outcome analysis of stakeholder influence. *Energy Research & Social Science, 4*, 53-63. doi:10.1016/j.erss.2014.09.001

Ryu, H.-J., Hong, K.-Y., Shin, S.-H., Kim, S.-H., & Kim, Y.-D. (2011). *Study on Analysis of Wave Energy Resources and Wave Energy Density Map of the Korean Sea Area*. Paper presented at the Joint Conference of the Korean Association of Ocean Science and Technology, Busan, Korea.

Schoer, K., Giegrich, J., Kovanda, J., Lauwigi, C., Liebich, A., Buyny, S., & Matthias, J. (2012). *Conversion of European Product Flows into Raw Material Equivalents*. Heidelberg, Germany: Institut für Energie- und Umweltforschung (IFEU) Retrieved from https://www.ifeu.de/nachhaltigkeit/pdf/RME_EU27-Report-final-2012831_end.pdf.

Scienceman, D. M. (1997). Emergy definition. *Ecological Engineering, 9*(3-4), 209-212. doi:10.1016/S0925-8574(97)10009-X

Seghezzo, L. (2009). The five dimensions of sustainability. *Environmental Politics, 18*(4), 539-556.

Seyfang, G., & Longhurst, N. (2013). Growing green money? Mapping community currencies for sustainable development. *Ecological Economics, 86*, 65-77. doi:10.1016/j.ecolecon.2012.11.003

Sgouridis, S. (2014). Defusing the Energy Trap: The Potential of Energy-Denominated Currencies to facilitate a Sustainable Energy Transition. *Frontiers in Energy Research, 2*, Article 8. doi:10.3389/fenrg.2014.00008

Shin, J.-S. (2011). *A study on the estimation of the scale of Korean energy poverty*. Retrieved from Uiwang, Korea:

Shobe, W. M., & Burtraw, D. (2012). *Rethinking Environmental Federalism in a Warming World*. Retrieved from Washington, DC: http://www.rff.org/documents/RFF-DP-12-04.pdf

Siche, J. R., Agostinho, F., Ortega, E., & Romeiro, A. (2008). Sustainability of nations by indices: Comparative study between environmental sustainability index, ecological footprint and the emergy performance indices. *Ecological Economics, 66*(4), 628-637. doi:http://dx.doi.org/10.1016/j.ecolecon.2007.10.023

SMG. (2014). *One Less Nuclear Power Plant, Phase 2*. Seoul, Korea: Seoul Metropolitan Government Retrieved from http://www.ieac.info/IMG/pdf/20140914olnpp2-lr.pdf.

Smuts, J. C. (1927). *Holism and Evolution* (2nd ed.). London, UK: Macmillan.

Sorman, A. H., & Giampietro, M. (2013). The energetic metabolism of societies and the degrowth paradigm: analyzing biophysical constraints and realities. *Journal of Cleaner Production, 38*, 80-93. doi:10.1016/j.jclepro.2011.11.059

Sovacool, B. K. (2011). An international comparison of four polycentric approaches to climate and energy governance. *Energy Policy, 39*(6), 3832-3844. doi:10.1016/j.enpol.2011.04.014

Statistics Korea. (2012). *Household Income and Expenditure Survey*. Daejeon, Korea: Korean Statistical Information Service (KOSIS) Retrieved from http://kosis.kr/statHtml/statHtml.do?orgId=101&tblId=DT_1L9H002&conn_path=I2.

Statistics Korea. (2015a). *2014 Birth Statistics (Final)*. Daejeon, Korea: Statistics Korea Retrieved from http://kostat.go.kr/portal/korea/kor_nw/2/1/index.board?bmode=read&aSeq=347963.

Statistics Korea. (2015b). *Household Sizes*. Daejeon, Korea: Statistics Korea Retrieved from http://www.index.go.kr/potal/stts/idxMain/selectPoSttsIdxSearch.do?idx_cd=2919.

Statistics Korea. (2015c). *Micro Data from the Household Income and Expenditure Survey*. Daejeon, Korea: Micro Data Service System (MDSS) Retrieved from http://mdss.kostat.go.kr/mdssext/DataProcessing/extraction/OfferRange.jsp?menu=3.

Stauffacher, M., Krütli, P., Flüeler, T., & Scholz, R. W. (2012). Learning from the Transdisciplinary Case Study Approach: A Functional-Dynamic Approach to Collaboration Among Diverse Actors in Applied Energy Settings. In D. Spreng, T. Flüeler, D. L. Goldblatt, & J. Minsch (Eds.), *Tackling Long-Term Global Energy Problems: The Contribution of Social Science* (pp. 227-245). Dordrecht, the Netherlands: Springer.

Steffen, W., & Stafford Smith, M. (2013). Planetary boundaries, equity and global sustainability: why wealthy countries could benefit from more equity. *Current Opinion in Environmental Sustainability, 3-4*, 403-408. doi:10.1016/j.cosust.2013.04.007

Steger, S., & Bleischwitz, R. (2011). Drivers for the use of materials across countries. *Journal of Cleaner Production, 19*(8), 816-826. doi:10.1016/j.jclepro.2010.08.016

Steinbach, J., & Staniaszek, D. (2015). *Discount rates in energy system analysis*. Buildings Performance Institute Europe (BPIE). Brussels, Belgium. Retrieved from http://bpie.eu/uploads/lib/document/attachment/142/Discount_rates_in_energy_system-discussion_paper_2015_ISI_BPIE.pdf

Steinberger, J. K., Krausmann, F., & Eisenmenger, N. (2010). Global patterns of materials use: A socioeconomic and geophysical analysis. *Ecological Economics, 69*(5), 1148-1158. doi:10.1016/j.ecolecon.2009.12.009

Stern, N. (2006). *Stern Review on the Economics of Climate Change*. London, UK: HM Treasury Retrieved from http://www.hm-treasury.gov.uk/stern_review_report.htm.

Stirling, A. (2010). Keep it complex. *Nature, 468*(7327), 1029-1031. doi:10.1038/4681029a

Strunz, S., Bartkowski, B., & Schindler, H. (2015). Is there a monetary growth imperative? *UFZ Discussion Papers, 2015*(5).

Su, M., Chen, B., Xu, L., Zhao, Y., Liu, G., Zhang, Y., & Yang, Z. (2011). An emergy-based analysis of urban ecosystem health characteristics for Beijing city. *International Journal of Exergy, 9*(2), 192-209. doi:10.1504/IJEX.2011.042068

Sweeney, S., Cohen, M. J., King, D., & Brown, M. T. (2007). Creation of a Global Emergy Database for Standardized National Emergy Synthesis. In M. T. Brown (Ed.), *Emergy Synthesis 4: Theory and Applications of the Emergy Methodology* (pp. 23.21-23.18). Gainesville, FL: The Center for Environmental Policy.

Tanter, R. (2013). After Fukushima: A Survey of Corruption in the Global Nuclear Power Industry. *Asian Perspective, 37*(4), 475-500. doi:10.5555/0258-9184-37.4.475

Tewksbury, J., & Wagner, G. (2014). The Role of Civil Society in Recalibrating Conservation Science Incentives. *Conservation Biology, 28*(5), 1437-1439. doi:10.1111/cobi.12288

Theis, T., & Tomkin, J. (Eds.). (2012). *Sustainability: A Comprehensive Foundation*. Urbana-Champaign, IL: University of Illinois Open Source Textbook Initiative.

Tilley, D. R. (2006). National Metabolism and Communications Technology Development in the United States, 1790-2000. *Environment and History, 12*(2), 165-190. Retrieved from http://www.ingentaconnect.com/content/whp/eh/2006/00000012/00000002/art00002

Tilley, D. R. (2015). Transformity dynamics related to maximum power for improved emergy yield estimations. *Ecological Modelling, 315*, 96–107. doi:10.1016/j.ecolmodel.2014.10.035

Tilley, D. R., Agostinho, F., Campbell, E., Ingwersen, W., Lomas, P., Winfrey, B., . . . P., Z. (2012). The ISAER transformity database Retrieved from http://emergydatabase.org/. from International Society for the Advancement of Emergy Research http://emergydatabase.org/

Ukidwe, N. U. (2005). *Thermodynamic input-output analysis of economic and ecological systems for sustainable engineering.* (Doctoral dissertation), The Ohio State University, Columbus, OH. Retrieved from http://etd.ohiolink.edu/view.cgi?acc_num=osu1117555725

Ukidwe, N. U., & Bakshi, B. R. (2007). Industrial and ecological cumulative exergy consumption of the United States via the 1997 input–output benchmark model. *Energy, 32*(9), 1560-1592. doi:10.1016/j.energy.2006.11.005

Ukidwe, N. U., & Bakshi, B. R. (2011). Exergy and Material Flow in Industrial and Ecological Systems. In B. R. Bakshi, T. G. Gutowski, & D. P. Sekulić (Eds.), *Thermodynamics and the Destruction of Resources* (pp. 292-333). New York, NY: Cambridge University Press.

Ulgiati, S. (2000). Energy, Emergy and Embodied Exergy: diverging or converging approaches? In M. T. Brown (Ed.), *Emergy Synthesis: Theory and Applications of the Emergy Methodology* (pp. 15-31). Gainesville, FL: The Center for Environmental Policy.

Ulgiati, S., Agostinho, F., Lomas, P. L., Ortega, E., Viglia, S., Zhang, P., & Zucaro, A. (2011). Criteria for Quality Assessment of Unit Emergy Values. In M. T. Brown (Ed.), *Emergy Synthesis 6: Theory and Applications of the Emergy Methodology* (pp. 599-610). Gainesville, FL: The Center for Environmental Policy.

Ulgiati, S., Ascione, M., Bargigli, S., Cherubini, F., Federici, M., Franzese, P., . . . Zucaro, A. (2010). Multi-method and Multi-scale Analysis of Energy and Resource Conversion and Use. In F. Barbir & S. Ulgiati (Eds.), *Energy Options Impact on Regional Security* (pp. 1-36). Dordrecht, The Netherlands: Springer.

Ulgiati, S., Ascione, M., Bargigli, S., Cherubini, F., Franzese, F., Raugei, M., . . . Zucaro, A. (2011). Material, energy and environmental performance of technological and social systems under a Life Cycle Assessment perspective. *Ecological Modelling, 222*(1), 176-189. doi:10.1016/j.ecolmodel.2010.09.005

Ulgiati, S., & Brown, M. T. (1998). Monitoring patterns of sustainability in natural and man-made ecosystems. *Ecological Modelling, 108*(1–3), 23-36. doi:10.1016/S0304-3800(98)00016-7

UN, EC, FAO, OECD, & World Bank. (2014). *System of Environmental-Economic Accounting 2012—Experimental Ecosystem Accounting*. (ST/ESA/STAT/Ser.F/112). New York, NY: United Nations Retrieved from http://unstats.un.org/unsd/envaccounting/seeaRev/eea_final_en.pdf.

UNCED. (1992). *Agenda 21*. Rio de Janerio, Brazil: United Nations Conference on Environment & Development Retrieved from http://sustainabledevelopment.un.org/content/documents/Agenda21.pdf.

UNDP. (2004). *World Energy Assessment: Overview 2004 Update*. New York, NY: United Nations Development Programme Retrieved from http://www.undp.org/content/dam/aplaws/publication/en/publications/environment-energy/www-ee-library/sustainable-energy/world-energy-assessment-overview-2004-update/World%20Energy%20Assessment%20Overview-2004%20Update.pdf.

UNDP. (2014). *Human Development Report 2014 - Sustaining Human Progress: Reducing Vulnerabilities and Building Resilience*. New York, NY: United Nations Development Programme Retrieved from http://hdr.undp.org/sites/default/files/hdr14-report-en-1.pdf.

UNSD. (2012). *National Accounts Main Aggregates Database (December 2012)*. New York, NY: United Nations Retrieved from http://unstats.un.org/unsd/snaama/dnlList.asp.

USGS. (2014). *Commodity Statistics and Information*. Reston, VA: United States Geological Survey Retrieved from http://minerals.usgs.gov/minerals/pubs/commodity/.

Valero, A., Valero, A., & Calvo, G. (2015). Using thermodynamics to improve the resource efficiency indicator GDP/DMC. *Resources, Conservation and Recycling, 94*, 110-117. doi:10.1016/j.resconrec.2014.12.001

Vardakoulias, O. (2013). *Discounting and time preferences*. The New Economics Foundation. London, UK. Retrieved from http://www.neweconomics.org/page/-/publications/Economics_in_policymaking_Briefing_5.pdf

Voß, J.-P., & Bornemann, B. (2011). The Politics of Reflexive Governance: Challenges for Designing Adaptive Management and Transition Management. *Ecology and Society, 16*(2), 9. Retrieved from http://www.ecologyandsociety.org/vol16/iss2/art9/

Walker, G., & Day, R. (2012). Fuel poverty as injustice: Integrating distribution, recognition and procedure in the struggle for affordable warmth. *Energy Policy, 49*, 69-75. doi:10.1016/j.enpol.2012.01.044

Walmsley, T. L., Aguiar, A. H., & Narayanan, B. (2012). Introduction to the Global Trade Analysis Project and the GTAP Data Base. *GTAP Working Paper, 67*. Retrieved from https://www.gtap.agecon.purdue.edu/resources/download/6122.pdf

Wang, Y.-D., Byrne, J., Boo, K.-J., Yun, S.-J., & Soh, Y. (1996). *A Spatially-Integrated Energy Planning Model for Korea's Sustainable Development*. Center for Energy and Environmental Policy. Newark, DE.

WCED. (1987). *Report of the World Commission on Environment and Development: Our Common Future*. (A/42/427). Geneva, Switzerland: World Commission on Environment and Development Retrieved from http://www.un-documents.net/our-common-future.pdf.

WEC. (2010). *2010 Survey of Energy Resources*. Retrieved from London, UK: http://www.worldenergy.org/documents/ser_2010_report_1.pdf

Wiedmann, T. O., Schandl, H., Lenzen, M., Moran, D., Suh, S., West, J., & Kanemoto, K. (2015). The material footprint of nations. *Proceedings of the National Academy of Sciences, 112*(20), 6271-6276. doi:10.1073/pnas.1220362110

Wolsink, M. (2010). Contested environmental policy infrastructure: Socio-political acceptance of renewable energy, water, and waste facilities. *Environmental Impact Assessment Review, 30*(5), 302-311. doi:10.1016/j.eiar.2010.01.001

World Bank. (2005). *World Development Report 2006: Equity and Development*. Washington, DC: World Bank Retrieved from http://go.worldbank.org/FFOT9IETN0.

World Bank. (2013). *World Development Indicators (April 16, 2013)*. Washington, DC: World Bank Retrieved from http://data.worldbank.org/data-catalog/world-development-indicators.

World Bank. (2014). *World Development Indicators (September, 24, 2014)*. Washington, DC: World Bank Retrieved from http://data.worldbank.org/data-catalog/world-development-indicators.

WSSD. (2002). *Johannesburg Declaration on Sustainable Development*. (A/CONF.199/20). Johannesburg, South Africa: World Summit on Sustainable Development Retrieved from http://www.un-documents.net/jburgdec.htm.

Yang, Z. F., Jiang, M. M., Chen, B., Zhou, J. B., Chen, G. Q., & Li, S. C. (2010). Solar emergy evaluation for Chinese economy. *Energy Policy, 38*(2), 875-886. doi:10.1016/j.enpol.2009.10.038

Yoon, J.-H., & Sim, K.-h. (2015). Why is South Korea's renewable energy policy failing? A qualitative evaluation. *Energy Policy, 86*, 369-379. doi:10.1016/j.enpol.2015.07.020

Yu, C.-S. (2006). *Environmental Capacity Assessment of Busan Using Emergy and Ecological Footprint Model.* (Master's thesis), Pusan National University, Busan, Korea.

Yun, S.-J. (2015). Challenges and Directives of Nuclear Governance in South Korea. *Environmental Law and Policy, 14*, 1-48.

Zhang, L. X., Chen, B., Yang, Z. F., Chen, G. Q., Jiang, M. M., & Liu, G. Y. (2009). Comparison of typical mega cities in China using emergy synthesis. *Communications in Nonlinear Science and Numerical Simulation, 14*(6), 2827-2836. doi:10.1016/j.cnsns.2008.03.018

Zhang, Y., Yang, Z., Liu, G., & Yu, X. (2011). Emergy analysis of the urban metabolism of Beijing. *Ecological Modelling, 222*(14), 2377-2384. doi:10.1016/j.ecolmodel.2010.09.017

Zhu, L., Li, H., Chen, J., John, R., Liang, T., & Yan, M. (2012). Emergy-based sustainability assessment of Inner Mongolia. *Journal of Geographical Sciences, 22*(5), 843-858. doi:10.1007/s11442-012-0967-5

Zweibel, K. (2010). Should solar photovoltaics be deployed sooner because of long operating life at low, predictable cost? *Energy Policy, 38*(11), 7519-7530. doi:10.1016/j.enpol.2010.07.040

Zwiers, M., & Koster, F. (2015). The local structure of the welfare state: Uneven effects of social spending on poverty within countries. *Urban Studies, 52*(1), 87-102. doi:10.1177/0042098014523688

Appendix

SUPPLEMENTARY TABLES

Table A-1: Renewable emergy inflows to South Korea (sej/yr)

No	1	2	3	4	5	6	7	8	9
Item	Sun	Wind, kinetic energy	Rain, chemical (land)	Rain, chemical (shelf)	Rain runoff, chemical	Rain runoff, geopotential	Waves	Earth cycle	Tide
1998	4.89E+20	7.08E+20	1.52E+22	4.44E+21	8.84E+21	7.27E+21	9.44E+21	6.34E+21	3.07E+22
1999	5.35E+20	7.43E+20	1.45E+22	4.22E+21	8.42E+21	6.92E+21	9.44E+21	6.34E+21	3.07E+22
2000	5.61E+20	7.66E+20	1.12E+22	3.27E+21	6.51E+21	5.35E+21	9.44E+21	6.35E+21	3.07E+22
2001	5.91E+20	7.27E+20	8.98E+21	2.61E+21	5.21E+21	4.28E+21	9.44E+21	6.35E+21	3.07E+22
2002	5.68E+20	8.71E+20	1.30E+22	3.79E+21	7.57E+21	6.22E+21	9.44E+21	6.35E+21	3.07E+22
2003	5.30E+20	6.82E+20	1.61E+22	4.69E+21	9.37E+21	7.70E+21	9.44E+21	6.35E+21	3.07E+22
2004	5.88E+20	7.78E+20	1.26E+22	3.65E+21	7.28E+21	5.98E+21	9.44E+21	6.36E+21	3.07E+22
2005	5.96E+20	9.21E+20	1.11E+22	3.23E+21	6.45E+21	5.30E+21	9.44E+21	6.36E+21	3.07E+22
2006	5.64E+20	7.75E+20	1.24E+22	3.60E+21	7.20E+21	5.92E+21	9.44E+21	6.36E+21	3.07E+22
2007	5.67E+20	7.42E+20	1.28E+22	3.73E+21	7.45E+21	6.12E+21	9.44E+21	6.36E+21	3.07E+22
2008	6.04E+20	7.43E+20	8.78E+21	2.55E+21	5.10E+21	4.19E+21	9.44E+21	6.37E+21	3.07E+22
2009	6.09E+20	8.05E+20	1.12E+22	3.26E+21	6.52E+21	5.36E+21	9.44E+21	6.37E+21	3.07E+22
2010	5.83E+20	8.06E+20	1.27E+22	3.69E+21	7.39E+21	6.07E+21	9.44E+21	6.38E+21	3.07E+22

Source: This study.

Table A-2: Non-renewable emergy inflows from within South Korea (sej/yr)

No	10	11	12	13	14	15	16
Item	Net forest loss	Net fisheries loss	Topsoil loss	Coal production	Natural gas production	Metallic minerals	Nonmetallic minerals
1998			6.53E+21	3.25E+21		7.88E+21	3.38E+23
1999			6.53E+21	3.13E+21		6.43E+21	3.60E+23
2000			6.53E+21	3.10E+21		5.59E+21	3.76E+23
2001			6.54E+21	2.85E+21		3.06E+21	3.84E+23
2002			6.54E+21	2.48E+21		4.66E+21	4.05E+23
2003			6.54E+21	2.46E+21		4.49E+21	4.24E+23
2004			6.54E+21	2.38E+21		5.86E+21	4.11E+23
2005			6.54E+21	2.11E+21	9.42E+20	5.76E+21	3.84E+23
2006			6.54E+21	2.11E+21	8.41E+20	6.33E+21	3.76E+23
2007			6.55E+21	2.15E+21	6.42E+20	7.60E+21	4.11E+23
2008			6.55E+21	2.07E+21	4.29E+20	9.26E+21	4.13E+23
2009			6.56E+21	1.88E+21	9.07E+20	9.05E+21	3.83E+23
2010			6.57E+21	1.55E+21	9.83E+20	1.01E+22	3.95E+23

Source: This study.

Table A-3: Imported resources into South Korea (sej/yr)

No	17							
		17-1	17-2	17-3	17-4	17-5	17-6	17-7
Item	Fuels	Anthracite	Bituminous for iron & steel	Bituminous for steam	Crude oil	Petroleum products	Natural gas (LNG)	Uranium
1998	4.62E+23	7.99E+20	1.98E+22	3.46E+22	2.59E+23	4.51E+22	2.51E+22	7.84E+22
1999	4.65E+23	1.15E+21	1.90E+22	3.60E+22	2.76E+23	4.54E+22	3.07E+22	5.69E+22
2000	4.90E+23	2.06E+21	2.16E+22	4.25E+22	2.82E+23	5.37E+22	3.45E+22	5.35E+22
2001	5.03E+23	3.15E+21	1.97E+22	4.67E+22	2.71E+23	5.63E+22	3.83E+22	6.72E+22
2002	4.99E+23	3.93E+21	1.95E+22	4.99E+22	2.50E+23	6.23E+22	4.14E+22	7.23E+22
2003	5.05E+23	4.70E+21	1.95E+22	5.06E+22	2.54E+23	6.03E+22	4.60E+22	6.97E+22
2004	5.22E+23	4.30E+21	2.09E+22	5.65E+22	2.61E+23	5.17E+22	5.25E+22	7.51E+22
2005	5.10E+23	4.62E+21	1.87E+22	5.57E+22	2.66E+23	4.51E+22	5.29E+22	6.63E+22
2006	5.38E+23	5.18E+21	1.82E+22	5.79E+22	2.81E+23	4.82E+22	5.97E+22	6.85E+22
2007	5.56E+23	5.51E+21	2.03E+22	6.48E+22	2.75E+23	5.29E+22	6.05E+22	7.65E+22
2008	5.79E+23	6.03E+21	2.31E+22	7.39E+22	2.73E+23	5.67E+22	6.45E+22	8.20E+22
2009	5.87E+23	6.55E+21	2.16E+22	7.80E+22	2.64E+23	7.16E+22	6.11E+22	8.48E+22
2010	6.24E+23	7.50E+21	2.68E+22	8.69E+22	2.75E+23	7.33E+22	7.72E+22	7.65E+22

Table A-3: Imported resources into South Korea (sej/yr) (continued)

No	18	19	20	21	22	23	24	25
Item	Metallic minerals	Nonmetallic minerals	Metal products	Cements	Food and agricultural products	Livestock, meat, fish	Plastics and rubber	Chemicals
1998	3.92E+23	4.14E+22	1.15E+23	3.09E+20	4.82E+22	5.23E+21	2.41E+21	2.36E+22
1999	4.15E+23	4.48E+22	1.72E+23	1.32E+21	5.16E+22	1.06E+22	3.24E+21	2.79E+22
2000	4.55E+23	4.98E+22	1.90E+23	1.47E+21	5.37E+22	1.14E+22	3.68E+21	3.05E+22
2001	5.29E+23	4.91E+22	1.77E+23	2.17E+21	5.40E+22	1.34E+22	3.71E+21	3.01E+22
2002	5.03E+23	5.11E+22	2.09E+23	2.68E+21	5.67E+22	1.62E+22	4.38E+21	3.26E+22
2003	5.03E+23	5.65E+22	2.19E+23	3.99E+21	5.65E+22	1.66E+22	4.71E+21	3.46E+22
2004	5.16E+23	6.16E+22	2.53E+23	7.17E+21	5.66E+22	1.52E+22	5.17E+21	3.78E+22
2005	5.09E+23	6.15E+22	2.53E+23	7.08E+21	5.77E+22	1.62E+22	5.47E+21	3.89E+22
2006	5.18E+23	6.43E+22	2.65E+23	6.62E+21	5.86E+22	1.83E+22	5.80E+21	3.77E+22
2007	5.41E+23	5.89E+22	3.11E+23	6.12E+21	6.07E+22	1.87E+22	6.02E+21	3.91E+22
2008	5.84E+23	6.21E+22	3.36E+23	4.22E+21	6.49E+22	1.62E+22	5.82E+21	3.89E+22
2009	5.00E+23	4.05E+22	2.69E+23	1.82E+21	6.00E+22	1.63E+22	5.22E+21	3.85E+22
2010	6.57E+23	5.71E+22	3.18E+23	1.70E+21	6.66E+22	1.78E+22	6.66E+21	4.35E+22

Table A-3: Imported resources into South Korea (sej/yr) (continued)

No	26	26-1	26-2	26-3	26-4	26-5	26-6	27	28
Item	Finished materials	Leather products	Lumber & wood products	Paper	Textile	Glass & ceramics	Others	Machinery, transportation equipment	Services in imports
1998	1.21E+21	2.17E+18	4.14E+17	8.88E+16	7.09E+18	8.50E+20	3.51E+20	8.70E+21	1.55E+23
1999	2.26E+21	2.50E+18	6.71E+17	1.12E+17	1.01E+19	1.68E+21	5.62E+20	1.15E+22	1.91E+23
2000	3.27E+21	2.70E+18	7.02E+17	1.05E+17	1.07E+19	2.51E+21	7.50E+20	1.59E+22	2.57E+23
2001	4.67E+21	2.51E+18	7.55E+17	9.88E+16	1.10E+19	3.89E+21	7.74E+20	1.70E+22	2.30E+23
2002	8.32E+21	2.55E+18	8.28E+17	1.07E+17	1.23E+19	7.28E+21	1.03E+21	2.13E+22	2.41E+23
2003	9.11E+21	2.27E+18	7.72E+17	1.05E+17	1.14E+19	7.87E+21	1.23E+21	2.23E+22	2.62E+23
2004	9.18E+21	2.19E+18	7.22E+17	1.11E+17	1.12E+19	7.76E+21	1.40E+21	2.97E+22	3.13E+23
2005	9.87E+21	2.16E+18	6.96E+17	1.06E+17	1.18E+19	8.08E+21	1.77E+21	2.83E+22	3.55E+23
2006	1.11E+22	2.05E+18	7.26E+17	1.04E+17	1.22E+19	8.85E+21	2.26E+21	3.28E+22	4.10E+23
2007	1.31E+22	2.05E+18	7.40E+17	1.08E+17	1.26E+19	1.06E+22	2.53E+21	4.12E+22	4.37E+23
2008	1.27E+22	1.90E+18	6.85E+17	1.07E+17	1.18E+19	1.03E+22	2.33E+21	4.44E+22	5.06E+23
2009	1.18E+22	1.99E+18	5.92E+17	9.78E+16	1.15E+19	9.90E+21	1.91E+21	4.52E+22	3.90E+23
2010	1.30E+22	2.04E+18	5.85E+17	1.12E+17	1.35E+19	1.06E+22	2.32E+21	4.65E+22	5.10E+23

Source: This study.

Table A-4: Exported resources from South Korea (sej/yr)

No	29	30	31	32	33	34	35	36	37
Item	Petroleum products	Metallic minerals	Nonmetallic minerals	Metal products	Cements	Food and agricultural products	Livestock, meat, fish	Plastics and rubber	Chemicals
1998	1.09E+23	2.90E+21	9.25E+21	1.51E+23	5.89E+21	2.88E+21	5.14E+21	2.20E+22	2.93E+22
1999	1.09E+23	2.15E+21	1.48E+22	1.23E+23	1.02E+22	2.71E+21	4.14E+21	2.16E+22	2.87E+22
2000	1.13E+23	6.48E+21	1.73E+22	1.25E+23	9.87E+21	2.82E+21	4.08E+21	2.20E+22	3.31E+22
2001	1.09E+23	5.74E+21	7.00E+21	1.26E+23	9.61E+21	3.15E+21	3.37E+21	2.19E+22	3.43E+22
2002	8.57E+22	9.82E+21	4.60E+21	1.20E+23	7.00E+21	3.26E+21	3.21E+21	2.40E+22	3.64E+22
2003	7.44E+22	2.68E+21	5.15E+21	1.33E+23	6.34E+21	3.31E+21	3.11E+21	2.64E+22	3.92E+22
2004	8.36E+22	1.08E+22	6.18E+21	1.42E+23	8.37E+21	3.35E+21	2.98E+21	2.78E+22	4.22E+22
2005	9.41E+22	1.56E+22	6.19E+21	1.50E+23	1.21E+22	3.45E+21	3.06E+21	2.98E+22	4.45E+22
2006	1.03E+23	3.74E+22	7.33E+21	1.68E+23	1.25E+22	3.30E+21	2.82E+21	3.01E+22	4.88E+22
2007	1.02E+23	2.95E+22	6.38E+21	1.76E+23	1.29E+22	3.49E+21	4.40E+21	3.20E+22	5.35E+22
2008	1.15E+23	2.58E+22	7.29E+21	1.93E+23	1.31E+22	3.61E+21	4.83E+21	3.28E+22	5.34E+22
2009	1.11E+23	3.09E+22	9.61E+21	1.90E+23	9.52E+21	4.06E+21	5.34E+21	3.69E+22	5.75E+22
2010	1.16E+23	3.00E+22	9.07E+21	2.23E+23	1.54E+22	4.84E+21	6.32E+21	3.82E+22	5.96E+22

Table A-4: Exported resources from South Korea (sej/yr) (continued)

No	38							39	40
		38-1	38-2	38-3	38-4	38-5	38-6		
Item	Finished materials	Leather products	Lumber & wood products	Paper	Textile	Glass & ceramics	Others	Machinery, transportation equipment	Services in exports
1998	1.66E+21	1.20E+18	1.61E+16	6.50E+16	2.43E+19	9.57E+20	6.73E+20	1.01E+23	3.98E+23
1999	1.77E+21	1.18E+18	1.50E+16	6.33E+16	2.55E+19	1.05E+21	6.87E+20	9.95E+22	4.27E+23
2000	1.93E+21	1.21E+18	1.43E+16	5.87E+16	2.60E+19	1.17E+21	7.39E+20	1.14E+23	5.15E+23
2001	1.94E+21	9.88E+17	1.09E+16	5.70E+16	2.40E+19	1.18E+21	7.34E+20	1.22E+23	4.43E+23
2002	1.88E+21	8.79E+17	7.72E+15	5.95E+16	2.40E+19	1.10E+21	7.58E+20	1.31E+23	4.61E+23
2003	2.12E+21	8.49E+17	7.84E+15	6.87E+16	2.42E+19	1.31E+21	7.92E+20	1.29E+23	5.53E+23
2004	2.37E+21	8.11E+17	1.02E+16	7.24E+16	2.31E+19	1.41E+21	9.38E+20	1.40E+23	7.28E+23
2005	2.42E+21	8.19E+17	5.65E+15	7.02E+16	2.03E+19	1.28E+21	1.13E+21	1.49E+23	7.83E+23
2006	2.68E+21	6.78E+17	4.96E+15	1.38E+17	1.90E+19	1.19E+21	1.47E+21	1.58E+23	8.92E+23
2007	2.67E+21	6.47E+17	5.24E+15	7.88E+16	1.93E+19	9.85E+20	1.66E+21	1.72E+23	1.03E+24
2008	2.65E+21	6.42E+17	4.63E+15	7.16E+16	1.84E+19	7.64E+20	1.86E+21	1.87E+23	1.22E+24
2009	2.84E+21	5.71E+17	4.44E+15	7.75E+16	1.78E+19	7.10E+20	2.11E+21	2.09E+23	9.26E+23
2010	3.29E+21	5.72E+17	4.12E+15	7.56E+16	1.96E+19	7.56E+20	2.51E+21	2.37E+23	1.31E+24

Source: This study.

Table A-5: Summary of annual emergy flows in South Korea

Flow	R	N	N0	N1+N2	N1	N2	N2(f)
Description	Renewable emergy flow	Total nonrenewable emergy flow	Dispersed nonrenewable production	Concentrated nonrenewable production	Concentrated nonrenewable use	Nonrenewable flow - exported without full use	Fuels exported without use
Unit	sej	sej	sej	sej	sej	sej	sej
1998	4.93E+22	3.55E+23	6.53E+21	3.49E+23	3.37E+23	1.21E+22	
1999	4.86E+22	3.76E+23	6.53E+21	3.69E+23	3.53E+23	1.70E+22	
2000	4.53E+22	3.92E+23	6.53E+21	3.85E+23	3.61E+23	2.38E+22	
2001	4.31E+22	3.97E+23	6.54E+21	3.90E+23	3.78E+23	1.27E+22	
2002	4.71E+22	4.19E+23	6.54E+21	4.12E+23	3.98E+23	1.44E+22	
2003	5.02E+22	4.38E+23	6.54E+21	4.31E+23	4.23E+23	7.83E+21	
2004	4.67E+22	4.26E+23	6.54E+21	4.20E+23	4.03E+23	1.70E+22	
2005	4.52E+22	3.99E+23	6.54E+21	3.92E+23	3.71E+23	2.18E+22	
2006	4.65E+22	3.92E+23	6.54E+21	3.85E+23	3.41E+23	4.47E+22	
2007	4.69E+22	4.28E+23	6.55E+21	4.22E+23	3.86E+23	3.59E+22	
2008	4.29E+22	4.32E+23	6.55E+21	4.25E+23	3.92E+23	3.31E+22	
2009	4.53E+22	4.01E+23	6.56E+21	3.95E+23	3.54E+23	4.05E+22	
2010	4.68E+22	4.14E+23	6.57E+21	4.08E+23	3.69E+23	3.90E+22	

Table A-5: Summary of annual emergy flows in South Korea (continued)

Flow	N2(m)	F(i)	G(i)	I	P2I	F(e)	G(e)
Description	Mineral & metal exported without use	Fuels, metals and minerals imports	Goods and electricity imports	Money ($) for imports	Imported services	Fuels, metals and minerals exports	Goods and electricity exports
Unit	sej	sej	sej	$	sej	sej	sej
1998	1.21E+22	8.96E+23	2.05E+23	9.33E+10	1.55E+23	1.21E+23	3.19E+23
1999	1.70E+22	9.25E+23	2.80E+23	1.20E+11	1.91E+23	1.26E+23	2.92E+23
2000	2.38E+22	9.95E+23	3.10E+23	1.60E+11	2.57E+23	1.37E+23	3.12E+23
2001	1.27E+22	1.08E+24	3.02E+23	1.41E+11	2.30E+23	1.22E+23	3.22E+23
2002	1.44E+22	1.05E+24	3.51E+23	1.52E+11	2.41E+23	1.00E+23	3.27E+23
2003	7.83E+21	1.06E+24	3.67E+23	1.79E+11	2.62E+23	8.23E+22	3.42E+23
2004	1.70E+22	1.10E+24	4.13E+23	2.24E+11	3.13E+23	1.01E+23	3.69E+23
2005	2.18E+22	1.08E+24	4.17E+23	2.61E+11	3.55E+23	1.16E+23	3.94E+23
2006	4.47E+22	1.12E+24	4.36E+23	3.09E+11	4.10E+23	1.48E+23	4.27E+23
2007	3.59E+22	1.16E+24	4.96E+23	3.57E+11	4.37E+23	1.37E+23	4.57E+23
2008	3.31E+22	1.23E+24	5.23E+23	4.35E+11	5.06E+23	1.48E+23	4.91E+23
2009	4.05E+22	1.13E+24	4.48E+23	3.23E+11	3.90E+23	1.52E+23	5.16E+23
2010	3.90E+22	1.34E+24	5.14E+23	4.25E+11	5.10E+23	1.55E+23	5.87E+23

Table A-5: Summary of annual emergy flows in South Korea (continued)

Flow	E	P1E	X	P2	P1	AREA	POP
Description	Money ($) for exports	Exported services	Gross Domestic Product (GDP)	World Emergy Money Ratio (EMR)	National Emergy Money Ratio (EMR)	Total land area	Total population
Unit	$	sej	$	sej/$	sej/$	m^2	people
1998	1.32E+11	3.98E+23	3.58E+11	1.66E+12	4.60E+12	9.94E+10	4.68E+07
1999	1.44E+11	4.27E+23	4.62E+11	1.60E+12	3.91E+12	9.94E+10	4.72E+07
2000	1.72E+11	5.15E+23	5.34E+11	1.60E+12	3.70E+12	9.95E+10	4.75E+07
2001	1.50E+11	4.43E+23	5.05E+11	1.63E+12	4.04E+12	9.95E+10	4.79E+07
2002	1.62E+11	4.61E+23	5.76E+11	1.59E+12	3.64E+12	9.96E+10	4.81E+07
2003	1.94E+11	5.53E+23	6.44E+11	1.47E+12	3.38E+12	9.96E+10	4.83E+07
2004	2.54E+11	7.28E+23	7.22E+11	1.40E+12	3.16E+12	9.96E+10	4.85E+07
2005	2.84E+11	7.83E+23	8.45E+11	1.36E+12	2.69E+12	9.96E+10	4.87E+07
2006	3.25E+11	8.92E+23	9.51E+11	1.33E+12	2.48E+12	9.97E+10	4.89E+07
2007	3.71E+11	1.03E+24	1.05E+12	1.23E+12	2.41E+12	9.97E+10	4.91E+07
2008	4.22E+11	1.22E+24	9.31E+11	1.16E+12	2.90E+12	9.98E+10	4.94E+07
2009	3.64E+11	9.26E+23	8.34E+11	1.21E+12	2.84E+12	9.99E+10	4.97E+07
2010	4.66E+11	1.31E+24	1.01E+12	1.20E+12	2.74E+12	1.00E+11	4.99E+07

Source: This study.

Table A-6: Summary of emergy synthesis indices

Number	Index-1	Index-2	Index-3	Index-4	Index-5	Index-6	Index-7	Index-8	Index-9
Index name	Total emergy inflows	Total emergy used (U)	Total imported emergy (IMP)	Total exported emergy (EXP)	Imports minus exports	Imports to exports	Imports to exports (excluding services)	Empower density (Use per Area)	Use per capita
Unit	sej	sej	sej	sej	sej	-	-	sej/m^2	sej/capita
Calcu- lation	R + N + IMP	R + N0 + N1 + IMP	F(i) + G(i) + Modified P2I	F(e) + G(e) + Modified P1E	IMP - EXP	IMP / EXP	[F(i) + G(i)] / [F(e) + G(e)]	U / Area	U / Population
1998	1.66E+24	1.65E+24	1.26E+24	8.38E+23	4.17E+23	1.49805	2.50212	1.66E+13	3.52E+16
1999	1.82E+24	1.80E+24	1.40E+24	8.45E+23	5.52E+23	1.65286	2.88646	1.81E+13	3.83E+16
2000	2.00E+24	1.98E+24	1.56E+24	9.64E+23	5.98E+23	1.62062	2.90810	1.99E+13	4.16E+16
2001	2.05E+24	2.04E+24	1.61E+24	8.88E+23	7.25E+23	1.81691	3.11280	2.05E+13	4.26E+16
2002	2.11E+24	2.10E+24	1.65E+24	8.88E+23	7.58E+23	1.85369	3.28915	2.11E+13	4.36E+16
2003	2.18E+24	2.17E+24	1.69E+24	9.78E+23	7.16E+23	1.73237	3.37119	2.18E+13	4.50E+16
2004	2.30E+24	2.28E+24	1.83E+24	1.20E+24	6.29E+23	1.52545	3.22261	2.29E+13	4.71E+16
2005	2.30E+24	2.27E+24	1.85E+24	1.29E+24	5.59E+23	1.43231	2.93272	2.28E+13	4.67E+16
2006	2.41E+24	2.36E+24	1.97E+24	1.47E+24	5.00E+23	1.34127	2.71063	2.37E+13	4.83E+16
2007	2.56E+24	2.53E+24	2.09E+24	1.63E+24	4.63E+23	1.28489	2.78224	2.54E+13	5.15E+16
2008	2.73E+24	2.70E+24	2.25E+24	1.85E+24	4.00E+23	1.21548	2.73944	2.70E+13	5.46E+16
2009	2.41E+24	2.37E+24	1.97E+24	1.59E+24	3.73E+23	1.23384	2.36142	2.37E+13	4.78E+16
2010	2.82E+24	2.78E+24	2.36E+24	2.05E+24	3.14E+23	1.15307	2.49469	2.78E+13	5.58E+16

Table A-6: Summary of emergy synthesis indices (continued)

Number	Index-10	Index-11	Index-12	Index-13	Index-14	Index-15	Index-16		Index-17
							a	b	
Index Name	Renewable flow per capita	Non-renewable flow per capita	Total fuel use	Fuel use per capita	Emergy Investment Ratio (EIR)	Environmental Loading Ratio (ELR)	National Effect of Investment (NEI)	National EYR	Emergy Sustainability Index (ESI)
Unit	sej/capita	sej/capita	sej	sej/capita	-	-	-	-	-
Calcu-lation	R / Population	N / Population	Production + Imports - Exported without use	Total fuel use / Population	IMP / (R+ N0 + N1)	(IMP + N0 + N1) / R	U / (N0 + N1+ IMP)	EXP / IMP	NEI / ELR
1998	1.05E+15	7.59E+15	4.66E+23	9.94E+15	3.19741	32.39793	1.31275	0.66753	0.04052
1999	1.03E+15	7.97E+15	4.68E+23	9.93E+15	3.42608	36.11279	1.29188	0.60501	0.03577
2000	9.54E+14	8.24E+15	4.93E+23	1.04E+16	3.77977	42.57119	1.26457	0.61705	0.02970
2001	9.00E+14	8.29E+15	5.06E+23	1.06E+16	3.77416	46.35141	1.26496	0.55039	0.02729
2002	9.80E+14	8.71E+15	5.02E+23	1.04E+16	3.64325	43.49126	1.27448	0.53946	0.02930
2003	1.04E+15	9.06E+15	5.07E+23	1.05E+16	3.52797	42.26743	1.28345	0.57724	0.03036
2004	9.62E+14	8.79E+15	5.24E+23	1.08E+16	4.00673	47.91242	1.24958	0.65555	0.02608
2005	9.29E+14	8.19E+15	5.13E+23	1.05E+16	4.38664	49.30844	1.22796	0.69817	0.02490
2006	9.51E+14	8.02E+15	5.41E+23	1.11E+16	4.99693	49.74898	1.20012	0.74556	0.02412
2007	9.55E+14	8.71E+15	5.59E+23	1.14E+16	4.75775	52.87630	1.21018	0.77828	0.02289
2008	8.68E+14	8.73E+15	5.82E+23	1.18E+16	5.10846	61.85892	1.19575	0.82272	0.01933
2009	9.13E+14	8.08E+15	5.90E+23	1.19E+16	4.84000	51.30849	1.20661	0.81048	0.02352
2010	9.39E+14	8.30E+15	6.26E+23	1.26E+16	5.59777	58.43407	1.17864	0.86725	0.02017

Table A-6: Summary of emergy synthesis indices (continued)

Number	Index-18	Index-19	Index-20	Index-21	Index-22	Index-23	Index-24		
							a	b	c
Index Name	Exported without use fraction	Indigenous fraction	Renewable fraction	Purchased fraction	Imported service fraction	Concentrated: Rural emergy use	Electricity fraction	Electricity consumption	Electricity from renewable energy
Unit	%	%	%	%	%	-	%	sej	sej
Calcu-lation	N2 / EXP	(N0 + N1+ R) / U	R / U	IMP / U	P2I / U	(IMP + N1) / (R + N0)	Electricity / U		
1998	0.01449	0.23824	0.02994	0.76176	0.09396	28.49658	0.17305	2.85E+23	6.34E+21
1999	0.02007	0.22593	0.02694	0.77407	0.10604	31.71919	0.17475	3.15E+23	6.16E+21
2000	0.02472	0.20922	0.02295	0.79078	0.13005	37.08468	0.18375	3.63E+23	6.13E+21
2001	0.01436	0.20946	0.02112	0.79054	0.11272	40.11431	0.19400	3.96E+23	3.62E+21
2002	0.01624	0.21537	0.02248	0.78463	0.11503	38.07238	0.20120	4.22E+23	5.06E+21
2003	0.00800	0.22085	0.02311	0.77915	0.12073	37.28511	0.20407	4.44E+23	7.61E+21
2004	0.01421	0.19973	0.02044	0.80027	0.13723	41.89846	0.20547	4.69E+23	6.81E+21
2005	0.01688	0.18564	0.01988	0.81436	0.15620	42.94890	0.21764	4.95E+23	5.88E+21
2006	0.03051	0.16675	0.01970	0.83325	0.17371	43.48943	0.21872	5.16E+23	5.76E+21
2007	0.02205	0.17368	0.01856	0.82632	0.17290	46.28164	0.21737	5.50E+23	6.54E+21
2008	0.01785	0.16371	0.01591	0.83629	0.18774	53.52576	0.21023	5.67E+23	6.19E+21
2009	0.02541	0.17123	0.01912	0.82877	0.16443	44.69879	0.24904	5.91E+23	6.78E+21
2010	0.01905	0.15157	0.01683	0.84843	0.18321	51.12614	0.23157	6.45E+23	8.45E+21

Table A-6: Summary of emergy synthesis indices (continued)

Number	Index-25	Index-26	Index-27	Index-28	Index-29	Index-30	Index-31
Index name	Soil loss per area	Soil loss fraction	Renewable Carrying Capacity	Emergy Self Sufficiency	Emergy use that is free	Purchased emergy	Energy consumption
Unit	sej/m^2	%	people	%	sej	sej	sej
Calcu-lation	Soil loss / Area	Soil loss / U	(R / U) × Population	(R + N0) / U	R + N0	U - (R + N0)	Fuel use + Renewable electricity
1998	6.57E+10	0.00396	1.40E+06	0.03390	5.59E+22	1.59E+24	4.72E+23
1999	6.57E+10	0.00362	1.27E+06	0.03056	5.51E+22	1.75E+24	4.74E+23
2000	6.57E+10	0.00331	1.09E+06	0.02626	5.19E+22	1.92E+24	4.99E+23
2001	6.57E+10	0.00320	1.01E+06	0.02432	4.96E+22	1.99E+24	5.09E+23
2002	6.57E+10	0.00312	1.08E+06	0.02559	5.37E+22	2.04E+24	5.07E+23
2003	6.57E+10	0.00301	1.12E+06	0.02612	5.68E+22	2.12E+24	5.15E+23
2004	6.57E+10	0.00287	9.91E+05	0.02331	5.32E+22	2.23E+24	5.31E+23
2005	6.57E+10	0.00288	9.68E+05	0.02275	5.18E+22	2.22E+24	5.19E+23
2006	6.57E+10	0.00277	9.63E+05	0.02248	5.31E+22	2.31E+24	5.47E+23
2007	6.57E+10	0.00259	9.12E+05	0.02115	5.35E+22	2.48E+24	5.65E+23
2008	6.57E+10	0.00243	7.86E+05	0.01834	4.94E+22	2.65E+24	5.88E+23
2009	6.57E+10	0.00277	9.49E+05	0.02188	5.19E+22	2.32E+24	5.97E+23
2010	6.57E+10	0.00236	8.39E+05	0.01918	5.34E+22	2.73E+24	6.35E+23

Source: This study.

Table A-7: Calculation of the Unit Emergy Values of “Services in Imports”

	Renewable sources			Nonrenewable sources from within system					Global emergy flows	Gross World Product	UEV of “Services in imports”
	Sun	Earth cycle	Tide	Soil erosion	Coal production	Oil production	Natural gas production	Minerals production			
Unit	sej/yr	sej/yr	sej/yr	sej/yr	sej/yr	sej/yr	sej/yr	sej/yr	sej/yr	Current US$	sej/$
1998	3.93E+24	4.07E+24	1.26E+24	1.06E+24	3.72E+24	8.06E+24	3.73E+24	2.40E+25	4.99E+25	3.00E+13	1.66E+12
1999	3.93E+24	4.07E+24	1.26E+24	1.06E+24	3.72E+24	7.91E+24	3.83E+24	2.41E+25	4.98E+25	3.12E+13	1.60E+12
2000	3.93E+24	4.07E+24	1.26E+24	1.06E+24	3.75E+24	8.22E+24	3.96E+24	2.50E+25	5.13E+25	3.20E+13	1.60E+12
2001	3.93E+24	4.07E+24	1.26E+24	1.06E+24	3.92E+24	8.22E+24	4.08E+24	2.54E+25	5.20E+25	3.19E+13	1.63E+12
2002	3.93E+24	4.07E+24	1.26E+24	1.06E+24	3.94E+24	8.18E+24	4.16E+24	2.61E+25	5.27E+25	3.32E+13	1.59E+12
2003	3.93E+24	4.07E+24	1.26E+24	1.06E+24	4.22E+24	8.48E+24	4.31E+24	2.75E+25	5.48E+25	3.73E+13	1.47E+12
2004	3.93E+24	4.07E+24	1.26E+24	1.06E+24	4.57E+24	8.87E+24	4.44E+24	3.04E+25	5.86E+25	4.20E+13	1.40E+12
2005	3.93E+24	4.07E+24	1.26E+24	1.06E+24	4.83E+24	8.96E+24	4.57E+24	3.32E+25	6.19E+25	4.55E+13	1.36E+12
2006	3.93E+24	4.07E+24	1.26E+24	1.06E+24	5.09E+24	9.01E+24	4.74E+24	3.62E+25	6.54E+25	4.93E+13	1.33E+12
2007	3.93E+24	4.07E+24	1.26E+24	1.06E+24	5.27E+24	8.98E+24	4.87E+24	3.87E+25	6.81E+25	5.56E+13	1.23E+12
2008	3.93E+24	4.07E+24	1.26E+24	1.06E+24	5.46E+24	9.06E+24	5.04E+24	4.11E+25	7.10E+25	6.10E+13	1.16E+12
2009	3.93E+24	4.07E+24	1.26E+24	1.06E+24	5.51E+24	8.83E+24	4.90E+24	4.03E+25	6.99E+25	5.79E+13	1.21E+12
2010	3.93E+24	4.07E+24	1.26E+24	1.06E+24	5.82E+24	9.03E+24	5.24E+24	4.54E+25	7.58E+25	6.32E+13	1.20E+12

Source: Estimates of transport of terrestrial organic carbon to the oceans by world rivers: Lal (2003); UEV of soil organic carbon: Cohen, Brown, and Shepherd (2006); Fossil fuel production: BP (2014); Mineral production: USGS (2014); UEVs for minerals: D. E. Campbell, Lu, and Lin (2014); Gross World Products: UNSD (2012).

Table A-8: Tide measurements at key points around South Korean parts of the Korean Peninsula

No	Place	Position		Spring rise	Neap rise	Mean sea level (Z0)	Spring range	Neap range	Mean tidal range	Distance between points	Area of a trapezoid
		Latitude	Longitude	m	m	m	m	m	m	km	m^2
1	Geojin	38°27′	128°28′	0.3	0.2	0.18	0.24	0.04	0.14		
2	Sokcho	38°12′	128°36′	0.3	0.2	0.2	0.2	0	0.1	30.134	3,616
3	Gisamun	38°01′	128°44′	0.3	0.3	0.23	0.14	0.14	0.14	23.488	2,819
4	Jumunjin	37°53′	128°50′	0.3	0.2	0.2	0.2	0	0.1	17.225	2,067
5	Mukho	37°33′	129°07′	0.3	0.2	0.19	0.22	0.02	0.12	44.664	4,913
6	Donghae	37°30′	129°08′	0.3	0.2	0.2	0.2	0	0.1	5.751	633
7	Samcheok	37°26′	129°12′	0.3	0.2	0.18	0.24	0.04	0.14	9.464	1,136
8	Imwon	37°14′	129°21′	0.2	0.2	0.12	0.16	0.16	0.16	25.893	3,884
9	Jukbyeon	37°03′	129°26′	0.2	0.2	0.16	0.08	0.08	0.08	21.683	2,602
10	Hupo	36°41′	129°28′	0.2	0.2	0.14	0.12	0.12	0.12	40.879	4,088
11	Chuksan	36°30′	129°27′	0.2	0.2	0.13	0.14	0.14	0.14	20.440	2,657
12	Ganggu	36°21′	129°24′	0.2	0.2	0.13	0.14	0.14	0.14	17.269	2,418
13	Bangeo-ri	36°12′	129°23′	0.2	0.1	0.12	0.16	0	0.08	16.746	1,842
14	Pohang	36°01′	129°24′	0.2	0.1	0.12	0.16	0	0.08	20.441	1,635
15	Guryongpo	35°59′	129°34′	0.2	0.1	0.12	0.16	0	0.08	15.444	1,236
16	Yangpo	35°53′	129°31′	0.2	0.1	0.12	0.16	0	0.08	11.996	960
17	Gampo	35°48′	129°30′	0.2	0.2	0.14	0.12	0.12	0.12	9.387	939
18	Jeongja-ri	35°37′	129°27′	0.3	0.3	0.21	0.18	0.18	0.18	20.880	3,132
19	Mipo	35°31′	129°27′	0.5	0.4	0.28	0.44	0.24	0.34	11.119	2,891
20	Ulsan	35°31′	129°23′	0.5	0.4	0.3	0.4	0.2	0.3	6.034	1,931
21	Bangeojin	35°29′	129°26′	0.5	0.4	0.31	0.38	0.18	0.28	5.850	1,697
22	Onsan	35°27′	129°21′	0.6	0.4	0.32	0.56	0.16	0.36	8.408	2,691
23	Go-ri	35°19′	129°17′	0.8	0.6	0.1	1.4	1	1.2	16.011	12,488
24	Daebyeon	35°13′	129°14′	0.9	0.6	0.49	0.82	0.22	0.52	12.010	10,329
25	Busan	35°06′	129°02′	1.2	0.9	0.65	1.1	0.5	0.8	22.335	14,741
26	Yeongdo	35°05′	129°03′	1.2	0.9	0.64	1.12	0.52	0.82	2.395	1,940
27	Dadaepo	35°03′	128°58′	1.4	1	0.74	1.32	0.52	0.92	8.442	7,344
28	Jinhae	35°09′	128°39′	2.1	1.5	1.11	1.98	0.78	1.38	30.880	35,512
29	Haengam Man	35°08′	128°41′	1.9	1.3	0.99	1.82	0.62	1.22	3.553	4,618
30	Masan	35°11′	128°34′	2	1.4	1.08	1.84	0.64	1.24	11.975	14,729
31	Unpungpo	35°06′	128°29′	2.1	1.5	1.12	1.96	0.76	1.36	11.970	15,561
32	Udupo	35°00′	128°29′	2	1.4	1.06	1.88	0.68	1.28	11.119	14,678
33	Tongyeong	34°49′	128°26′	2.6	1.8	1.41	2.38	0.78	1.58	20.889	29,872
34	Goseong Man	34°55′	128°21′	2.9	2.1	1.58	2.64	1.04	1.84	13.470	23,034

Table A-8: Tide measurements at key points around South Korean parts of the Korean Peninsula (continued)

No	Place	Position		Spring rise	Neap rise	Mean sea level (Z0)	Spring range	Neap range	Mean tidal range	Distance between points	Area of a trapezoid
		Latitude	Longitude	m	m	m	m	m	m	km	m^2
35	Samcheonpo	34°55′	128°04′	3	2.2	1.65	2.7	1.1	1.9	25.834	48,309
36	Jinju Man	35°03′	128°03′	3.4	2.5	1.89	3.02	1.22	2.12	14.904	29,956
37	Seosang-ri	34°48′	127°50′	3.3	2.4	1.84	2.92	1.12	2.02	34.102	70,592
38	Cosmos Wharf	34°51′	127°43′	3.5	2.5	1.9	3.2	1.2	2.2	12.013	25,348
39	Yeosu	34°45′	127°46′	3.3	2.3	1.81	2.98	0.98	1.98	12.020	25,122
40	Nokdong	34°31′	127°08′	3.7	2.8	2.09	3.22	1.42	2.32	63.488	136,500
41	Maryang	34°27′	126°49′	3.6	2.6	2.04	3.12	1.12	2.12	29.956	66,503
42	Eoranjin	34°21′	126°29′	3.6	2.7	2.03	3.14	1.34	2.24	32.542	70,940
43	Okmae	34°34′	126°22′	3.7	2.8	2.07	3.26	1.46	2.36	26.360	60,628
44	Usuyeong	34°35′	126°19′	3.5	2.8	2.03	2.94	1.54	2.24	4.939	11,359
45	Wollae-ri	34°45′	126°17′	4.3	3.4	2.44	3.72	1.92	2.82	18.782	47,517
46	Yanghwa-ri	34°45′	126°19′	4	3.2	2.26	3.48	1.88	2.68	3.045	8,375
47	Mokpo	34°47′	126°24′	4.3	3.4	2.34	3.92	2.12	3.02	8.466	24,129
48	Naesan-ri	34°47′	126°23′	4.1	3.2	2.31	3.58	1.78	2.68	1.522	4,338
49	Hampyeong Man	35°09′	126°21′	5.6	4.4	3.15	4.9	2.5	3.7	40.884	130,421
50	Daejang-ri	35°49′	126°24′	6.1	4.7	3.36	5.48	2.68	4.08	74.268	288,903
51	Gunsan (outer)	35°58′	126°38′	6.6	5	3.62	5.96	2.76	4.36	26.833	113,234
52	Janghang	36°00′	126°41′	6.9	5.1	3.74	6.32	2.72	4.52	5.829	25,881
53	Maryang-ri	36°08′	126°31′	6.5	4.8	3.55	5.9	2.5	4.2	21.077	91,894
54	Daecheon	36°20′	126°30′	7	5.4	3.84	6.32	3.12	4.72	22.289	99,410
55	Boryeong	36°24′	126°29′	7	5.2	3.82	6.36	2.76	4.56	7.562	35,086
56	Muchangpo	36°15′	126°32′	6.7	5.9	3.66	6.08	4.48	5.28	17.270	84,970
57	Anheung	36°40′	126°08′	6.5	4.8	3.55	5.9	2.5	4.2	58.534	277,453
58	Mohang-ri	36°47′	126°08′	6.6	5.1	3.63	5.94	2.94	4.44	12.973	56,042
59	Cheollipo	36°48′	126°09′	6.7	5	3.68	6.04	2.64	4.34	2.374	10,423
60	Hakampo	36°54′	126°13′	6.7	5.2	3.66	6.08	3.08	4.58	12.603	56,209
61	Oji-ri	36°57′	126°19′	7.3	5.4	3.98	6.64	2.84	4.74	10.485	48,859
62	Samgilpo	37°00′	126°27′	7.8	5.8	4.29	7.02	3.02	5.02	13.084	63,852
63	Hanjin-ri	36°57′	126°48′	8.9	6.8	4.82	8.16	3.96	6.06	31.585	174,980
64	Pyeongtaek	37°00′	126°47′	8.6	6.4	4.66	7.88	3.48	5.68	5.754	33,773
65	Incheon	37°28′	126°36′	8.6	6.4	4.64	7.92	3.52	5.72	54.370	309,909
66	Wolgot-ri	37°46′	126°31′	6.2	4.8	3.39	5.62	2.82	4.22	34.156	169,757
	Total									1,288.148	2,935,304

Source: MOE and NIER (2012).

Table A-9: Calculation of the annual average transformity of electricity

Technology	Transfor-mity [a, b] sej/J	Share of each technology in total electricity sales 1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Bituminous coal	167,885	33.87%	33.04%	35.53%	37.69%	38.77%	37.11%	37.17%	36.76%	36.61%	38.50%	41.15%	44.39%	41.85%
Nuclear	122,324	42.69%	44.28%	41.90%	40.15%	40.99%	41.81%	39.54%	41.61%	40.24%	36.62%	37.00%	35.03%	32.39%
LNG	135,433	13.30%	12.90%	10.96%	10.95%	11.22%	11.48%	15.00%	14.31%	16.16%	17.61%	16.71%	14.29%	19.44%
Oil (diesel & heavy oil)	271,414	5.006%	5.115%	7.375%	7.859%	6.192%	6.442%	5.637%	4.951%	4.384%	4.439%	2.300%	3.194%	2.703%
Anthracite coal	167,885	3.099%	2.878%	2.703%	2.509%	2.178%	2.133%	1.658%	1.550%	1.468%	1.475%	1.623%	1.812%	1.746%
Hydro	63,314	2.037%	1.787%	1.542%	0.834%	0.633%	0.819%	0.753%	0.631%	0.880%	0.963%	0.771%	0.686%	0.828%
Product-gas	145,178					0.003%	0.171%	0.192%	0.120%	0.136%	0.198%	0.172%	0.197%	0.595%
Wind	62,631					0.001%	0.001%	0.006%	0.031%	0.062%	0.097%	0.108%	0.168%	0.185%
Solar	52,279							0.000004%	0.0001%	0.001%	0.005%	0.047%	0.097%	0.101%
Landfill gas	145,178					0.013%	0.031%	0.044%	0.038%	0.044%	0.082%	0.106%	0.104%	0.091%
Fuel cell	160,832									0.0001%	0.001%	0.003%	0.020%	0.044%
Waste-burnup	145,178						0.0005%	0.001%	0.002%	0.004%	0.008%	0.007%	0.014%	0.016%
Bio	57,455								0.00004%	0.000002%	0.0005%	0.001%	0.004%	0.006%
Ocean (tidal)	57,455												0.00000001%	0.000001%
Total		100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Average transformity	(sej/J)	1.47E+05	1.47E+05	1.51E+05	1.53E+05	1.51E+05	1.51E+05	1.50E+05	1.49E+05	1.48E+05	1.49E+05	1.47E+05	1.50E+05	1.48E+05

[a] Numbers are expressed relative to the 9.26E+24 sej/yr planetary baseline.
[b] References of transformities:

Energy source	Source of Transformity
Anthracite coal	(Häyhä, Franzese, & Ulgiati, 2011)
Bio	An average of solar and wind power transformities
Bituminous coal	(Häyhä et al., 2011)
Fuel cell	(Ulgiati et al., 2010)
Hydro	An average of transformities from (Brown & Ulgiati, 2002) and (Häyhä et al., 2011)
Landfill Gas	(Marchettini, Ridolfi, & Rustici, 2007)
LNG	An average of transformities from (Häyhä et al., 2011) and (Ulgiati et al., 2010)
Nuclear	An average of transformities from (D. E. Campbell & Ohrt, 2009) and (Häyhä et al., 2011)
Ocean (tidal)	An average of wind and solar power transformities
Oil (diesel + heavy oil)	An average of transformities from (Brown & Ulgiati, 2002) and (Brown et al., 2012)
Product-gas	Assume the transformity of coal (anthracite & bituminous)
Solar	An average of transformities from (Paoli, Vassallo, & Fabiano, 2008) and (Ulgiati et al., 2010)
Waste-burnup	(Marchettini et al., 2007)
Wind	An average of transformities from (Brown & Ulgiati, 2002) and (Häyhä et al., 2011)

Table A-10: Calculation of air pollutant transformities

Chemical species	Transformity (sej/g)	Calculation	References
SO_X	1.88E+10	= 32.065 / (32.065+15.9994×2) × [Transformity of S]	Sulfur (S) transformity (3.76E+10 sej/g) from (D. E. Campbell, Lu, & Lin, 2014)
NO_X	4.32E+09	= 14.0067×2 / (14.0067×2+15.9994) × [Transformity of N]	Nitrogen (N) transformity (6.79E+09 sej/g) from (D. E. Campbell, Lu, & Lin, 2014)
TSP	2.04E+10	= [Transformity of PM_{10}]	PM_{10} transformity (2.04E+10 sej/g) from (E. T. Campbell, 2012)
CO	3.33E+09	= [Global emergy baseline] ÷ [Global CO budget]	Annual global CO budget (2.78E+15 g of CO) from (IPCC, 2001, p. 257); Methodology adopted from (D. E. Campbell, 2015)
NH_3	3.45E+09	= [Transformity of NH_3]	NH_3 transformity (3.45E+09 sej/g) from (D. E. Campbell, Lu, & Lin, 2014)
VOC	9.13E+09	= [Global emergy baseline] ÷ [Global VOC budget]	Annual global VOC budget (5.71E+14 g of C = 1.01E+15 g of VOC) from (IPCC, 2001, p. 258); Percentage of carbon in VOC (56.3%) from (Gillenwater, 2008); Methodology adopted from (D. E. Campbell, 2015)

Table A-11: References for 10 country emergy evaluation comparison

Country	Short citation	Full citation
Brazil	Pereira and Ortega (2013)	Pereira, L., & Ortega, E. (2013). Assessment of Services in Emergy Accounting of Nations In M. T. Brown (Ed.), *Emergy Synthesis 7: Theory and Applications of the Emergy Methodology* (pp. 453–470). Gainesville, FL: The Center for Environmental Policy.
China	Lou and Ulgiati (2013)	Lou, B., & Ulgiati, S. (2013). Identifying the environmental support and constraints to the Chinese economic growth—An application of the Emergy Accounting method. *Energy Policy*, *55*, 217–233. doi: 10.1016/j.enpol.2012.12.009
Denmark	Haden (2003)	Haden, A. C. (2003). *Emergy Evaluations of Denmark and Danish Agriculture: Assessing the Limits of Agricultural Systems to Power Society*. Uppsala, Sweden: Centrum för uthålligt lantbruk (CUL).
Japan	Gasparatos and Gadda (2009)	Gasparatos, A., & Gadda, T. (2009). Environmental support, energy security and economic growth in Japan. *Energy Policy*, *37*(10), 4038–4048. doi: 10.1016/j.enpol.2009.05.011
Korea, South	This study	
Portugal	Oliveira et al. (2013)	Oliveira, C., Martins, C., Gonçalves, J., & Veiga, F. (2013). Solar Emergy Evaluation of the Portuguese Economy. In M. T. Brown (Ed.), *Emergy Synthesis 7: Theory and Applications of the Emergy Methodology* (pp. 437–451). Gainesville, FL: The Center for Environmental Policy.
Spain	Lomas et al. (2008)	Lomas, P. L., Álvarez, S., Rodríguez, M., & Montes, C. (2008). Environmental accounting as a management tool in the Mediterranean context: The Spanish economy during the last 20 years. *Journal of Environmental Management*, *88*(2), 326–347. doi: 10.1016/j.jenvman.2007.03.009

Taiwan	Huang et al. (2006)	Huang, S.-L., Lee, C.-L., & Chen, C.-W. (2006). Socioeconomic metabolism in Taiwan: Emergy synthesis versus material flow analysis. *Resources, Conservation and Recycling*, *48*(2), 166-196. doi: 10.1016/j.resconrec.2006.01.005
United Kingdom	Gasparatos et al. (2009)	Gasparatos, A., El-Haram, M., & Horner, M. (2009). Assessing the sustainability of the UK society using thermodynamic concepts: Part 1. *Renewable and Sustainable Energy Reviews*, *13*(5), 1074–1081. doi: 10.1016/j.rser.2008.03.004
United States	D. E. Campbell, Lu, and Walker (2014)	Campbell, D. E., Lu, H., & Walker, H. A. (2014). Relationships among the Energy, Emergy and Money Flows of the United States from 1900 to 2011. *Frontiers in Energy Research*, *2*, Article 41. doi: 10.3389/fenrg.2014.00041

Table A-12: Fulfillment results of Renewable Portfolio Standards in 2012

Group	Power supplier	Division	Mandatory supply (REC)	Fulfillment (REC)	Ratio
Public utilities	Korea Hydro & Nuclear Power	Solar	43,332	38,679	89.3%
		Non-solar	1,966,924	1,585,937	80.6%
		Subtotal	2,010,256	1,624,616	80.8%
	Korea South-East Power	Solar	43,056	41,859	97.2%
		Non-solar	790,632	322,532	40.8%
		Subtotal	833,688	364,391	43.7%
	Korea Midland Power	Solar	43,056	42,369	98.4%
		Non-solar	695,094	349,932	50.3%
		Subtotal	738,150	392,301	53.1%
	Korea Western Power	Solar	43,056	39,530	91.8%
		Non-solar	717,647	398,784	55.6%
		Subtotal	760,703	438,314	57.6%
	Korea Southern Power	Solar	43,056	42,797	99.4%
		Non-solar	790,845	524,249	66.3%
		Subtotal	833,901	567,046	68.0%
	Korea East-West Power	Solar	43,056	43,056	100.0%
		Non-solar	691,227	379,785	54.9%
		Subtotal	734,283	422,841	57.6%
Independent power producers	Korea District Heating Corporation	Solar	2,484	2,174	87.5%
		Non-solar	101,831	81,137	79.7%
		Subtotal	104,315	83,311	79.9%
	Korea Water Resources Corporation	Solar	2,484	1,804	72.6%
		Non-solar	-	-	-
		Subtotal	2,484	1,804	72.6%
	SK E&S	Solar	2,484	2,041	82.2%
		Non-solar	87,668	26,794	30.6%
		Subtotal	90,152	28,835	32.0%
	GS EPS	Solar	2,484	2,484	100.0%
		Non-solar	78,637	54,539	69.4%
		Subtotal	81,121	57,023	70.3%
	GS Power	Solar	2,484	2,419	97.4%
		Non-solar	48,815	34,173	70.0%
		Subtotal	51,299	36,592	71.3%
	POSCO Energy	Solar	2,484	2,484	100.0%
		Non-solar	140,099	97,325	69.5%
		Subtotal	142,583	99,809	70.0%
	MPC Yulchon	Solar	2,484	2,484	100.0%
		Non-solar	34,860	34,860	100.0%
		Subtotal	37,344	37,344	100.0%
Total		Solar	276,000	264,180	95.7%
		Non-solar	6,144,279	3,890,047	63.3%
		Total	6,420,279	4,154,227	64.7%

Note. 1 REC (Renewable Energy Certificate) = 1 MWh (multiplied with different weights according to the power sources)
Source: J.-H. Kim and Lee (2013).