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Analysis of the Relationship between Energy (Useful Work) and Economic Growth of the Republic of Korea

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Abstract

Analysis of the Relationship between Energy (Useful Work) and Economic Growth of the Republic of Korea

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Over the last half-century, Korea has achieved remarkable economic growth enabling it to become the world's 11th largest economy. Various efforts have been made to identify the driving forces of its rapid economic growth and to verify the relationship between Korea's energy consumption and economic development. However, conventional energy analyses have limitations because they did not consider the actual services energy provides for economic activities.

"Useful work" measures the amount of exergy finally used at the end-use stage, which focuses on the result of an energy use rather than energy input. Moreover, useful work considers both quality of energy and the thermodynamic second-law efficiency,

which gives better insights into the role of energy in an economy. Useful work has been an important factor for Korea's economic development, and it has been affected by industrial structures, economic shocks, and energy policies.

Korea's industrialization in the 1960s and 1970s created a rapid increase in useful work consumption. The oil shocks in the 1970s slightly slowed the growth of useful work consumption and contributed to the diversification of Korea's energy portfolio. In the late 1980s and 1990s, the growth of Korea's useful work consumption accelerated again due to the increasing demand in the industry and transportation sectors. After Korea's financial crisis in 1997, the growth rates of GDP and useful work consumption have slowed down.

Korea's rapid industrialization has increased the shares of mechanical drive and high temperature heat uses, and aggregate exergy efficiency has improved faster than that in other countries. As a result, Korea became able to produce more goods and services with less energy (exergy) inputs, and energy (exergy) intensity has declined. However, useful work intensity has been more stable because of improved exergy efficiency. This shows that Korea's useful work consumption is more closely related to its economic growth than energy consumption.

In this paper, Korea's energy sectors are briefly introduced, and the processes for estimating useful work from IEA data are summarized. The evolution of Korea's useful work consumption, exergy efficiency, useful work intensity, and their relationships to Korea's economic development are also presented.

Table of Contents

List of Tables

List of Figures

1. INTRODUCTION

Over the last half-century, Korea has achieved remarkable economic growth, enabling it to become the world's 11th largest economy and the 6th largest exporter (WB, 2017; WTO, undated). Korea's real GDP has increased at an annual growth rate of 11% between 1953 and 1997, before Korea's financial crisis (The Bank of Korea, 2017a). This rapid economic growth is unprecedented worldwide, and it has stimulated curiosity about its driving forces. Various factors such as high savings rates, human capital, and strategic economic policies have been identified (World Economic Forum, 2015), and analysts have also studied the role of energy in Korea's economic development.

Previous analyses of the relationship between the energy and economy of Korea have mainly focused on verifying the causality between them by applying econometric analysis techniques (Kim, 1998; Lee and Oh, 2001; Glasure, 2002; Oh and Lee, 2003; Mo and Kim, 2003; Oh and Lee, 2004; Jung and Kang, 2013). However, energy consumption data used in these analyses have limitations in that they did not measure the actual services energy provides for economic activities. Primary energy or final energy consumption data do not reflect the quality of energy. Even final energy consumption data do not consider the conversion efficiency at the end-use stage, and actual work finally used are much less than original energy contents because, most of energy are lost during conversion processes. Therefore, another approach is required to understand better the relationship between energy consumption and economic growth (Ayres and Warr, 2004).

In this respect, useful work – useful exergy of a given energy end-use - could be a good measure of the actual services energy provides for an economy. Useful work focuses on the result of energy use rather than on energy input, and it measures the amount of exergy finally used at the end-use stage. The exergy values of physical work used by a car or an exergy value of heat flow used for residential heating are examples of useful work, and they are smaller than the energy contents of consumed gasoline or natural gas. Since useful work analysis considers both the quality of energy used for an economy and the improvement in thermodynamic second-law efficiency, useful work gives better insights into the role of energy in economic growth (Serrenho et al., 2016).

Previously, various efforts have been made to verify the relationship between useful work and economic growth around the world. Ayres et al. (2003) and Ayres and Warr (2005) emphasized useful work as a growth engine for the U.S. economy. Serrenho et al. (2014) suggested a systematic approach to estimate useful work and analyzed useful work intensities of 15 EU countries. Comprehensive analyses for useful work have also been conducted for the U.S., U.K., Japan, China, Austria, and Portugal (Brockway et al., 2015; Warr and Ayres, 2010; Warr et al., 2008, 2010; Serrenho et al., 2016). Recently, Santos et al. (2016) adopted quality adjusted capital, labor, and useful work as factors of production and tested various economic growth models for Portugal.

However, in Korea, there is little analysis regarding useful work and its relationship to economic growth. Therefore, a useful work analysis of Korea would be helpful for verifying the changes in Korea's useful work consumption during its economic development and for clarifying the driving forces of Korea's rapid economic growth. In this paper, Korea's energy sectors will be briefly introduced, and the processes for estimating useful work consumption from the energy statistics data of International Energy Agency (IEA) will be suggested. Finally, the evolution of Korea's useful work consumption, aggregate exergy efficiency, and useful work intensity, and their relationship to Korea's economic development will be presented.

2. CURRENT STATUS OF ENERGY SECTOR OF KOREA

2.1. TOTAL ENERGY SUPPLY AND DEMAND

In 2015, Korea was the world's 9th largest energy consuming country. Korea's total primary energy supply (TPES) in 2015 was 287.5 million tonne of oil equivalent (Mtoe), which was about 12.6% of the U.S. total and 1.4% of the world total (British Petroleum, 2016). Around 83% (238.7Mtoe) of it came from fossil fuels such as oil (38.1%, 109.6Mtoe), coal (29.7%, 85.5Mtoe), and LNG (15.2%, 43.6Mtoe). The share of nuclear was 12.1% (34.8Mtoe) and renewable energy including hydro-electric power was 4.9% (14.1Mtoe) (Figure 1).

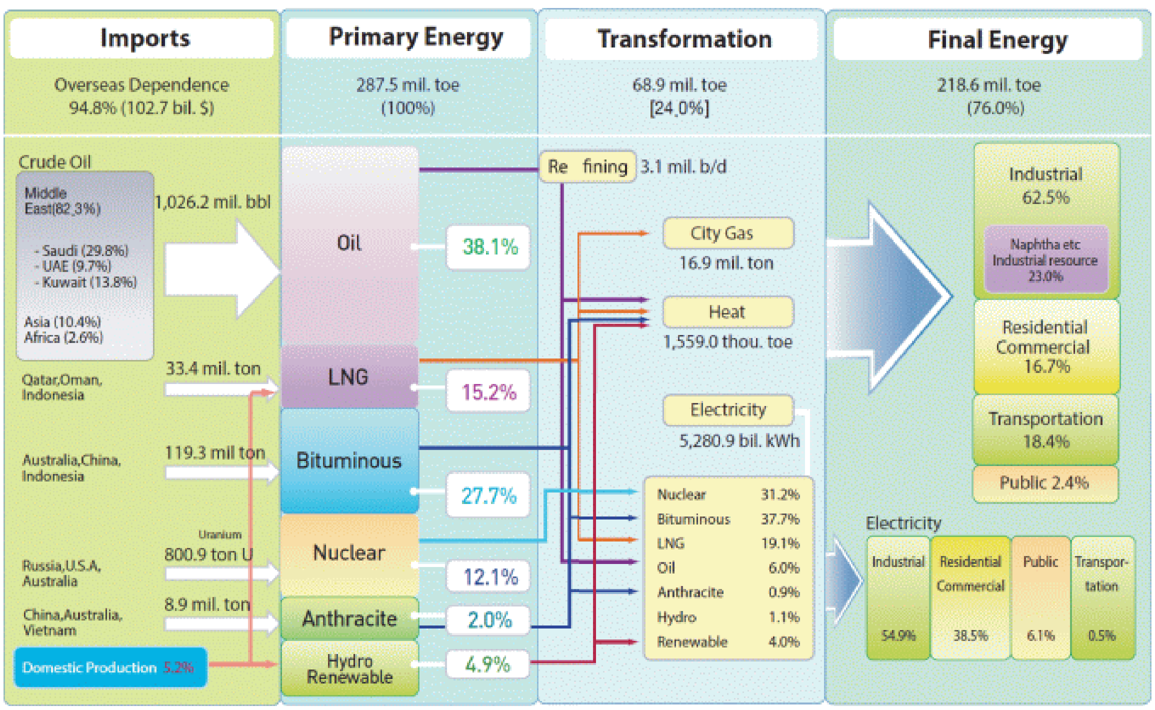


Figure 1: Energy Balance Flow of Korea in 2015 (KEEI, 2017a)

Korea's coal consumption in the residential sector has been mostly replaced by LNG and electricity, but coal has remained as a major source for power generation. Petroleum consumption increased significantly in the 1980s and 1990s, but its share in TPES is now decreasing. Nuclear power and LNG have become major sources for power generation since they first started being used in the late 1970s and mid-1980s. Renewable energy has grown sharply over the last 10 years, but its share has been negligible until now (Figure 2).

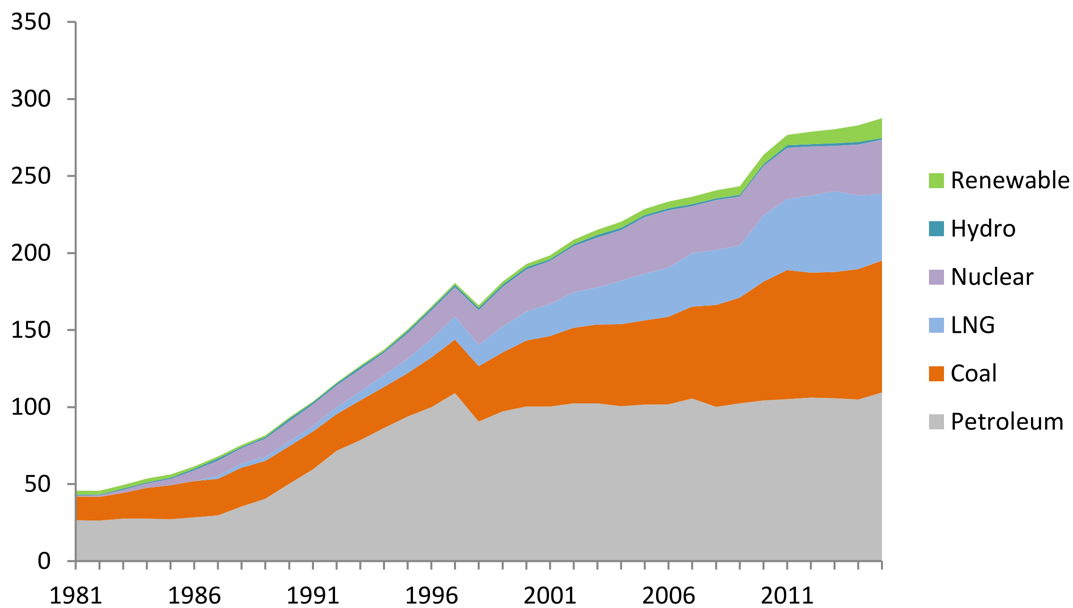


Figure 2: Korea's Total Primary Energy Supply by Source (Mtoe) (KEEI, 2017a)

Korea relies on imports for about 95% of its energy supply because it lacks domestic energy resources. Korea's energy production accounted for just 4.8% of TPES in 2015 when nuclear was not included (KEEI, 2017). Korea's coal (anthracite) production recorded a historical high in 1987, but it has decreased sharply after the 1990s due to decreasing residential demand and reduced government subsidies. LNG began to be produced in 2004 in the gas field in the East Sea, but LNG production is insignificant. Renewable energy became the largest source of domestic energy production which has increased by 224% over the past 10 years, as a result of various governmental support (Figure 3).

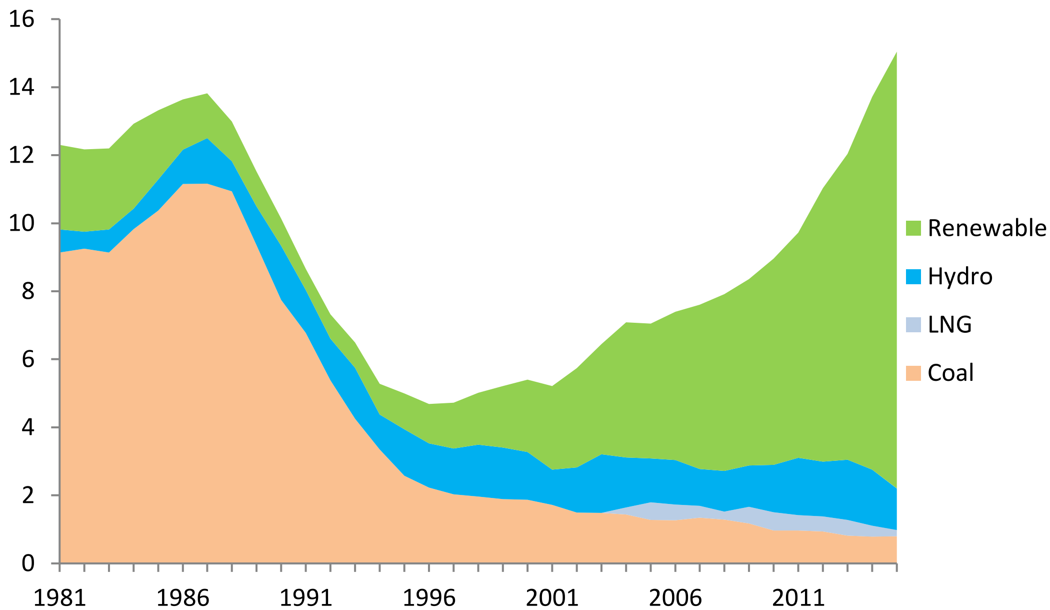


Figure 3: Korea's Domestic Energy Production (Mtoe) (KEEI, 2017a)

As a result, Korea has became one of the largest energy importers in the world. It ranked as the world's 10th importer for natural gas, 2nd for coal, and 3rd for crude oil and refined petroleum products in 2015 (KEEI, 2017b). Korea imported 314.8 Mtoe, costing 102.7 billion U.S. dollars, of energy resources, mainly oil (60.2%, 189.6 Mtoe), coal (26.0%, 81.7 Mtoe), and LNG (13.8%, 43.5 Mtoe) (Figure 4). Since Korea has no international oil or natural gas pipelines, it relies exclusively on tanker shipments of crude oil and LNG. Korea's energy export in 2015 was 66 Mtoe, mostly petroleum products refined in domestic refineries.

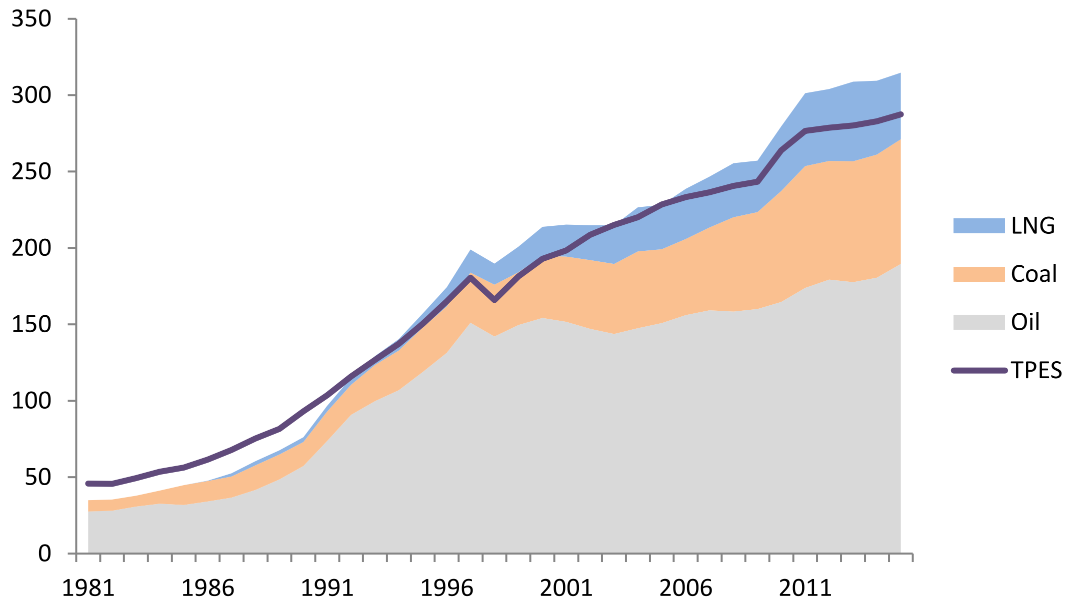


Figure 4: Korea's Energy Import by Type (Mtoe) (KEEI, 2017a)

In 2015, Korea's total final energy consumption (TFC) was 218.6 Mtoe. The industry sector consumed the largest share of TFC (62.5%, 136.7 Mtoe), and the transport sector was the second (18.4%, 40.3 Mtoe). The residential and commercial sector accounted for 16.7% (36.4 Mtoe), and the public sector for 2.4% (5.2 Mtoe). Korea's TFC has increased in line with its economic development. Since Korea's industrialization began in earnest after the 1960s, industry has been a main driver for the increase in energy consumption. The growth rate of TFC has slowed due to the 1st and 2nd oil shocks in the 1970s, and it took several years to recover its past trend. In the late 1980s and early 1990s, the increase of TFC accelerated by the growing energy demand, especially in the industry and transport sectors caused by Korea's economic boom and increasing use of cars. After

Korea's financial crisis in 1997 and the global financial crisis in 2007, the Korean economy lost its fast growth engine, and increasing of TFC has also slowed (Figure 5).

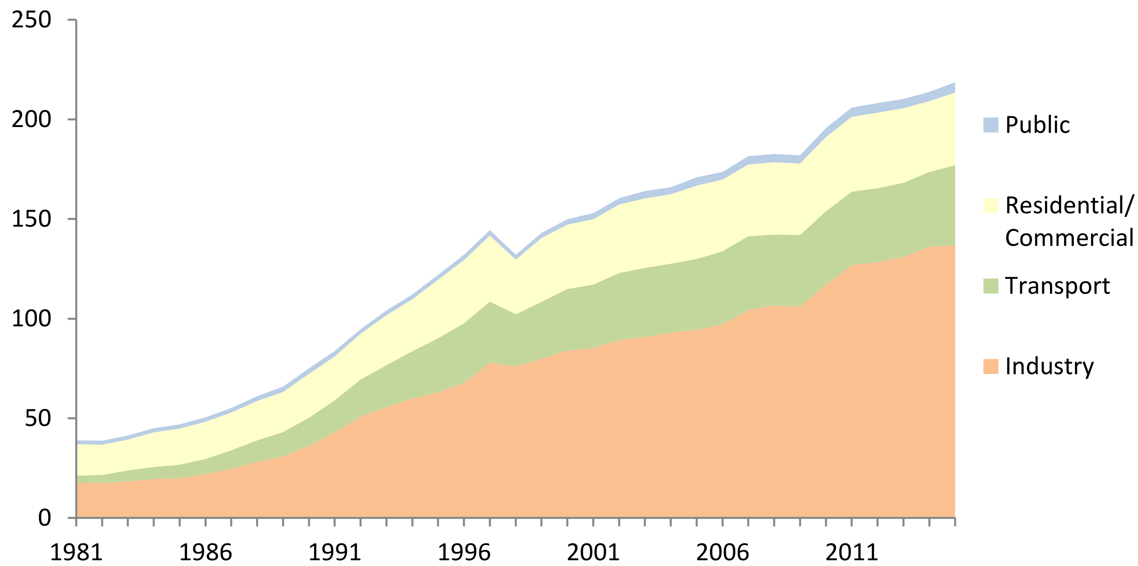


Figure 5: Korea's Total Final Energy Consumption by Sector (Mtoe) (KEEI, 2017a)

2.2. Energy Industry

2.2.1. Petroleum

In 2015, Korea consumed 856.2 million barrels (107.3 Mtoe) of petroleum products which made it the 8th largest oil consumer in the world. Around 52.6% (62.2 Mtoe) of petroleum products were used for industry, 36.2% (38.4 Mtoe) for transportation, 9.8% (5.3 Mtoe) for the residential and commercial sector, and 1.4% (1.5 Mtoe) for the public sector. The demand for petroleum products increased rapidly in the 1980s and 1990s, mainly due to the growing demand in the industry and transportation sectors, but the growth rate declined after the economic crisis of Korea in 1997. And the share of oil in Korea's TFC is currently decreasing (Figure 6).

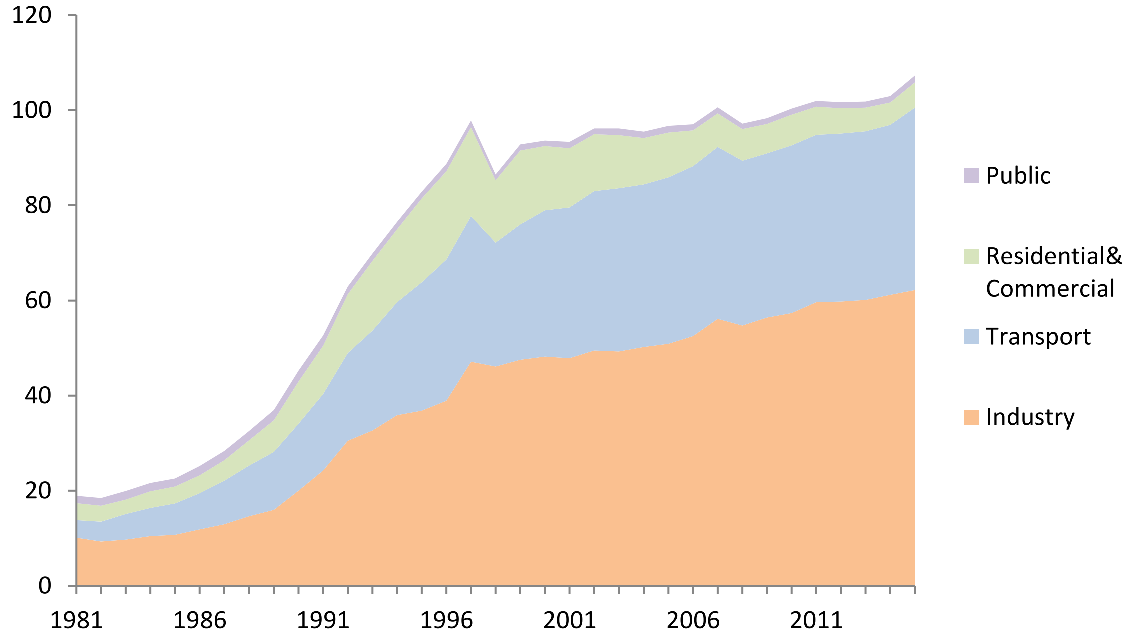


Figure 6: Korea's Petroleum Consumption by Sector (Mtoe) (KEEI, 2017a)

Korea has no oil fields and thus it depends almost entirely on imports of crude oil to meet its demand, making Korea the 5th largest oil importers in the world. In 2015, Korea imported 1,026 million barrels (MMbbl) of crude oil, which was about a 4.6-fold increase compared to 1981. Korea depends heavily on crude oil from the Middle East, which accounted for more than 82% of Korea's oil imports in 2015. This dependence on the Middle East declined slightly after the second oil crisis in 1978, but Korea's reliance on the Middle East has rebounded since the 1990s. Saudi Arabia has been the leading supplier of oil for more than 20 years. In 2015, it supplied 30% of Korea's crude oil import, followed by the U.A.E. at 14% and Iran, Kuwait, and Oman at 12% each (Figure 7). More than 70% of crude oil from Middle East was imported by long-term contracts, whereas around 70%

of crude oil from other regions such as Asia, Africa, and America was imported by spot contracts (KEEI, 2017b).

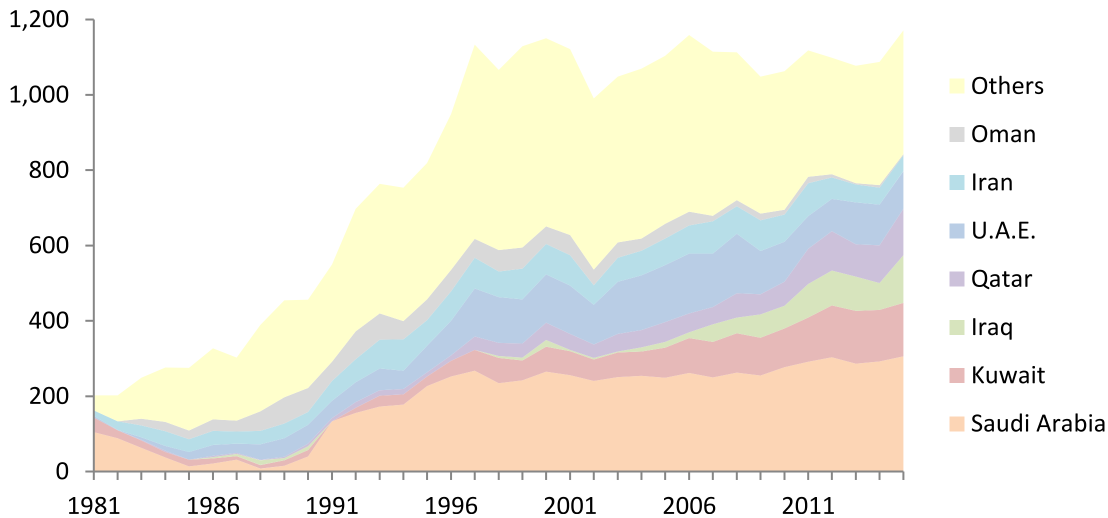


Figure 7: Korea’s Crude Oil Import by Country (MMbbl) (KEEI, 2017b)

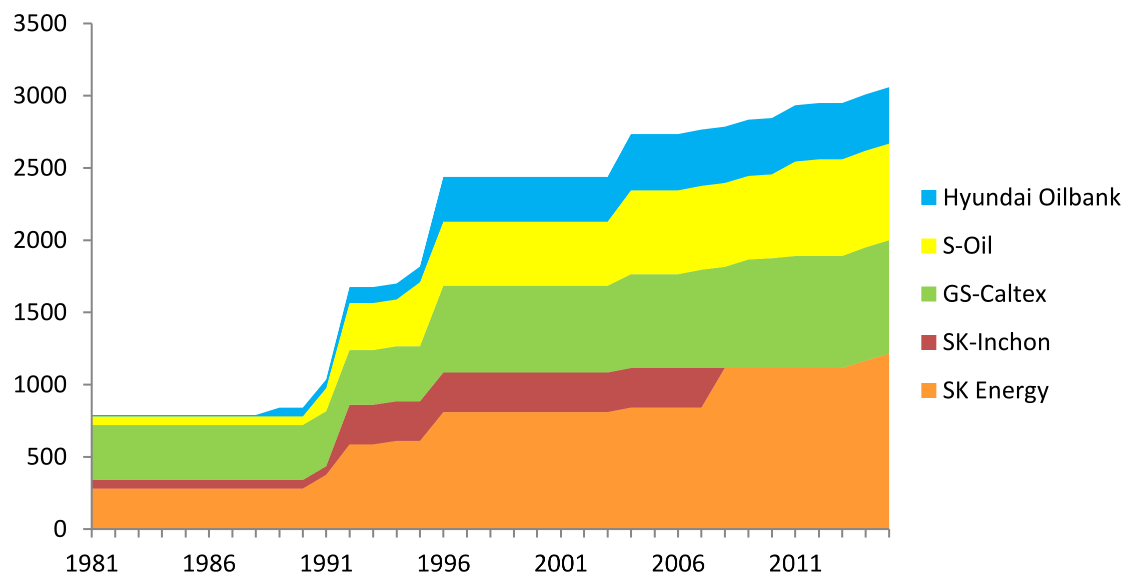


Figure 8: Korea’s Refinery Capacity by Company (1,000 BPSD) (KEEI, 2017a)

Korea has the third largest refinery capacity in the world (US EIA, 2017). Korea's downstream sector includes four large international oil companies. SK Energy is the largest, having the domestic market share of 23.7% in 2014, followed by GS Caltex (20.5%), S-Oil (11.2%), and Hyundai Oilbank (13.5%) (Korea Petroleum Association, 2015). These companies have historically focused on refining imported oil and marketing petroleum products. Recently, the share of domestic marketing has decreased and export of petroleum products has increased.

Korea National Oil Corporation (KNOC), a state owned company, is responsible for overseas resource development and for managing strategic oil reserves. KNOC and private oil companies have begun to actively invest in overseas E&P projects in response to high oil prices in the 2000s. However, Korea's upstream sectors are still in their infancy, and they are reducing investment after the global financial crisis in 2007. Daehan Oil Pipeline Corporation (DOPCO) owns and manages domestic oil pipelines, although most of Korea's petroleum products are distributed by tankers or trucks (US EIA, 2017).

In 2015, Korea produced 1,117 MMbbl of petroleum products which is more than a six-fold increase compared to 1981. Recently, Korean refineries have tried to increase the production of light, clean petroleum products by upgrading refining facilities to increase their refining margin. As a result, the shares of light (LPG, gasoline, naphtha) and medium (kerosene, jet fuel, and diesel) distillates in total petroleum production have increased from 70.1% in 2005 to 83.8% in 2015. The proportions of each petroleum product were 29.9% for diesel, 22.4% for naphtha, 14.1% for gasoline, and 13.6% for jet oil in 2015 (Figure 9).

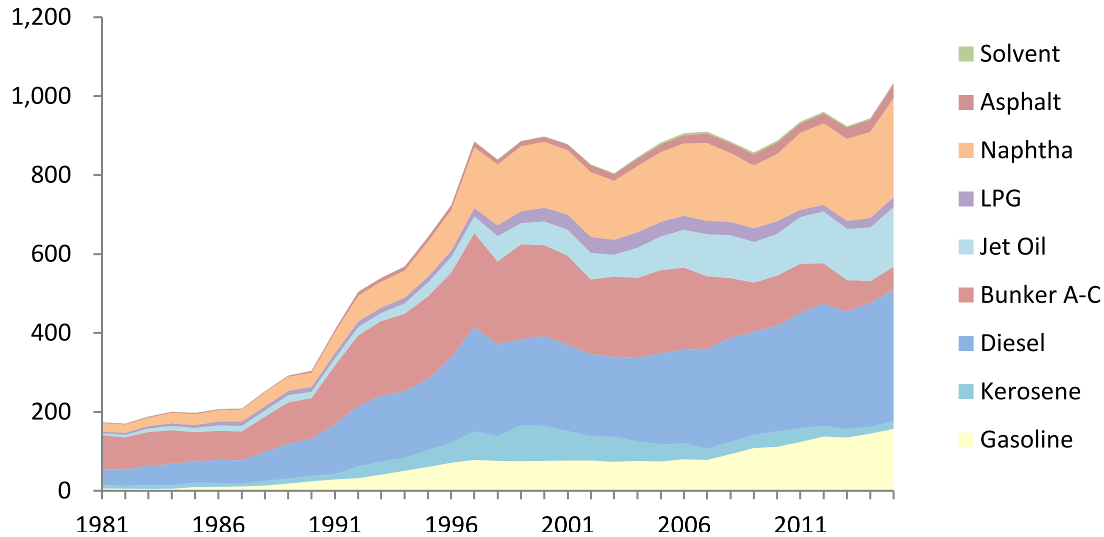


Figure 9: Korea's Petroleum Products Production (MMbbl) (KEEI, 2017a)

In Korea, petroleum products are distributed to consumers by direct sales, wholesalers, retailers, and gas stations. In 2015, refiners directly supplied 64.7% of products to consumers, mainly in industrial sector. Around 24.2% was distributed to wholesalers, 10.6% to gas stations, and 0.4% to retailers. Wholesalers sold them to consumers or redistributed to gas stations and retailers. As a result, gas stations accounted for 29.4% of petroleum products distribution, retailers for 3.31%, and wholesalers for 2.54%. In 2015, there were 12,178 gas stations and 608 wholesalers in Korea (Table 1).

	SK	**GS-Caltex**	**Hyundai Oilbank**	**S-oil**	**Others**	**Total**
Gas stations	3774	2,568	2,244	2,049	1,543	12,178
Wholesalers	36	22	15	12	523	608

Table 1: Korea's Gas Stations and Wholesalers in 2015 (KNOC, 2016)

Korea is one of the Asia's largest exporters of petroleum products. Korea's refining capacity exceeds domestic demand, and surplus petroleum products are exported to other countries, mostly in Asia. In 2015, Korea exported 477.4 MMbbl of refined petroleum products valued at US $30 billion. This constituted approximately 43% of Korea's total petroleum production in quantity, and even more in monetary value, since most of exported products were high-valued light and medium distillates such as gasoline and diesel. Korea's exports of petroleum products have increased rapidly over the last 10 years due to Korea's increasing production and slowing domestic demand (Figure 10)

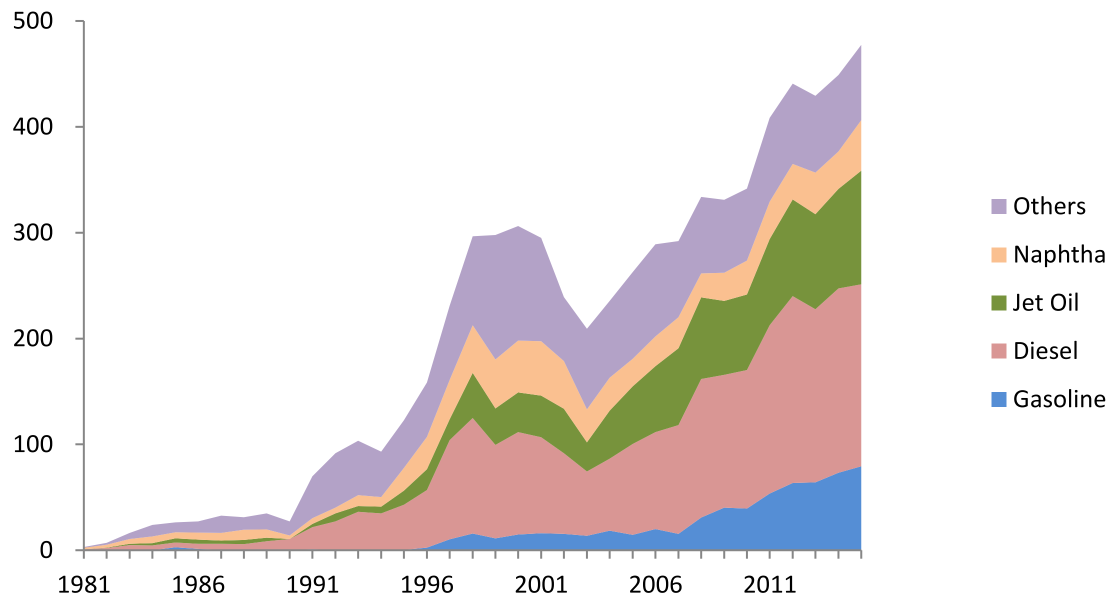


Figure 10: Korea's Petroleum Products Export (MMbbl) (KEEI, 2017b)

2.2.2. Natural Gas

Natural gas accounted for 15.2% of TPES of Korea in 2015, and it is increasing rapidly. Korea's natural gas consumption has increased 15-fold between 1988 and 2013 due to the growing demand in power generation and dissemination of city gas. However, natural gas consumption has fallen by 16 % between 2013 and 2015 due to the decreased prices of LPG and coals (US EIA, 2017). In 2015, Korea consumed 33.4 million tones (22.1Mtoe) of natural gas, among which 50.6% was used for city gas manufacturing, 43.6% for power generation, and 4.6% for district heating (Figure 11). City gas was used in residential (41.2%), industrial (34.3%), commercial (8.9%), and transportation (5.8%) sectors (KEEI, 2017b). The number of households using city gas in 2015 was 16.6 million, which was about 80.8% of the total households in Korea (Korea City Gas Association, 2016).

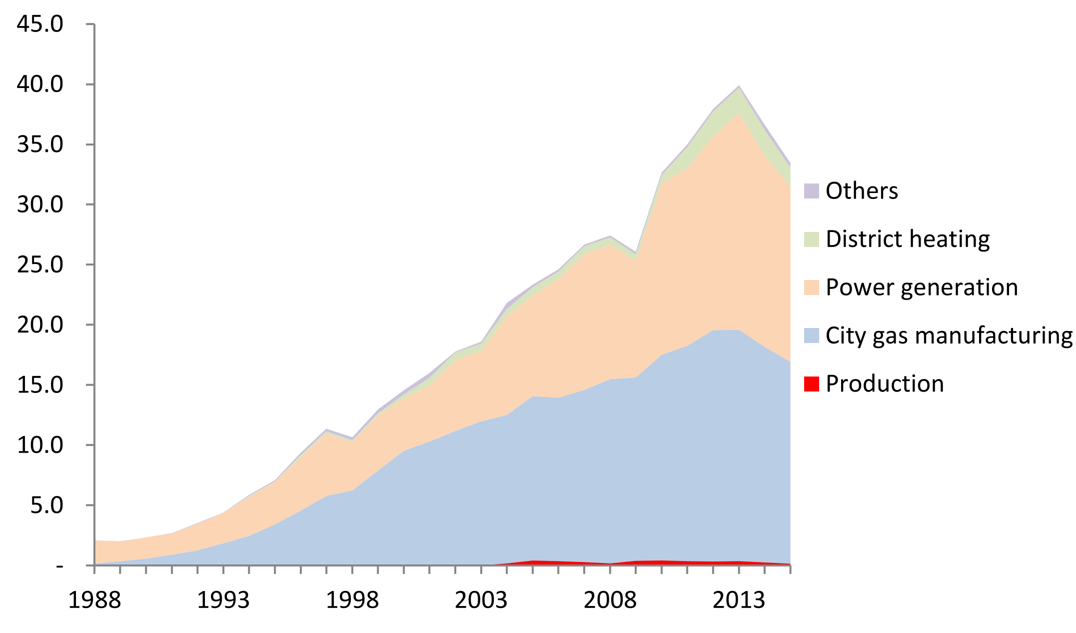


Figure 11: Korea's Natural Gas Consumption and Production (million tonnes) (KEEI, 2017b)

Korea has only one gas field (Donghae-1) located in Block 6-1 in the Ulleung Basin (Figure 12). It was discovered in 1998 and began to produce natural gas in 2004. In 2015, it produced 144.3 thousand tonnes of natural gas, down from a high of 414.8 thousand tonnes in 2010 (KNOC, undated a). The natural gas production of Korea is negligible, accounting for only 0.4% of domestic demand in 2015 (KEEI, 2017b). Therefore, Korea heavily depends on imports to satisfy its increasing natural gas demand. Since Korea does not have any international natural gas pipeline connections, it must import natural gas via LNG tankers. As a result, Korea became the second largest LNG importer in the world, after Japan (US EIA, 2017).

Figure 12: Donghae-1 Gas Field in the East Sea in Korea (KNOC, undated b)

In 2015, Korea imported 33.4 million tonnes of LNG, which was about a 50% increase compared to 2005. Indonesia was the Korea's first source of LNG, and it has been a major LNG supplier, along with Malaysia and Brunei, in the 1990s. However, Korea's LNG imports have been diversified as LNG consumption increases. In 2015, 37.3% of LNG was imported from Qatar, which became the largest LNG supplier for Korea. The shares from Oman, Indonesia, and Malaysia were each about 11% (Figure 13).

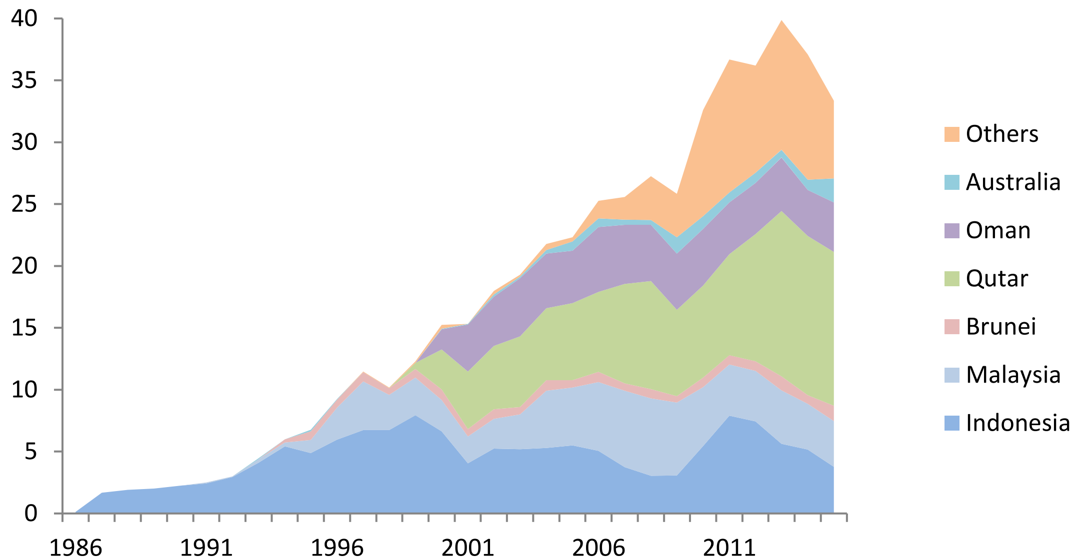


Figure 13: Korea's Natural Gas Import (million tonnes) (KEEI, 2017b)

In domestic LNG distribution, the Korea Gas Corporation (KOGAS) plays an important role. KOGAS is in charge of wholesale distribution of LNG in Korea, making it the largest single LNG importer in the world. KOGAS imports LNG and distributes it to power generation plants, gas-utility companies, and city gas companies. KOGAS operates four LNG terminals (Pyongtaek, Incheon, Tong-Yeong, and Samcheok) and nationwide trunk lines with a total length of 4,672km (KOGAS, undated a). KOGAS recently started to invest in overseas gas development projects using its purchasing power, but it is still insignificant compared to major resource development companies worldwide.

Other private companies are allowed to import LNG if they use the gas for their own purposes and if the price does not exceed KOGAS' long-term contract prices (US EIA, 2017). However, the proportion of direct imports was only about 6% of total LNG imports in 2015. Korea has 34 private city gas distribution companies that have monopoly control in their region (Korea City Gas Association, 2016). These local companies purchase wholesale natural gas from KOGAS and sell it to consumers through pipelines. The total length of pipeline used for city gas distribution was 41,235km in 2015. The wholesale price of LNG is controlled by the central government and the retail price is determined by the local government (Figure 14).

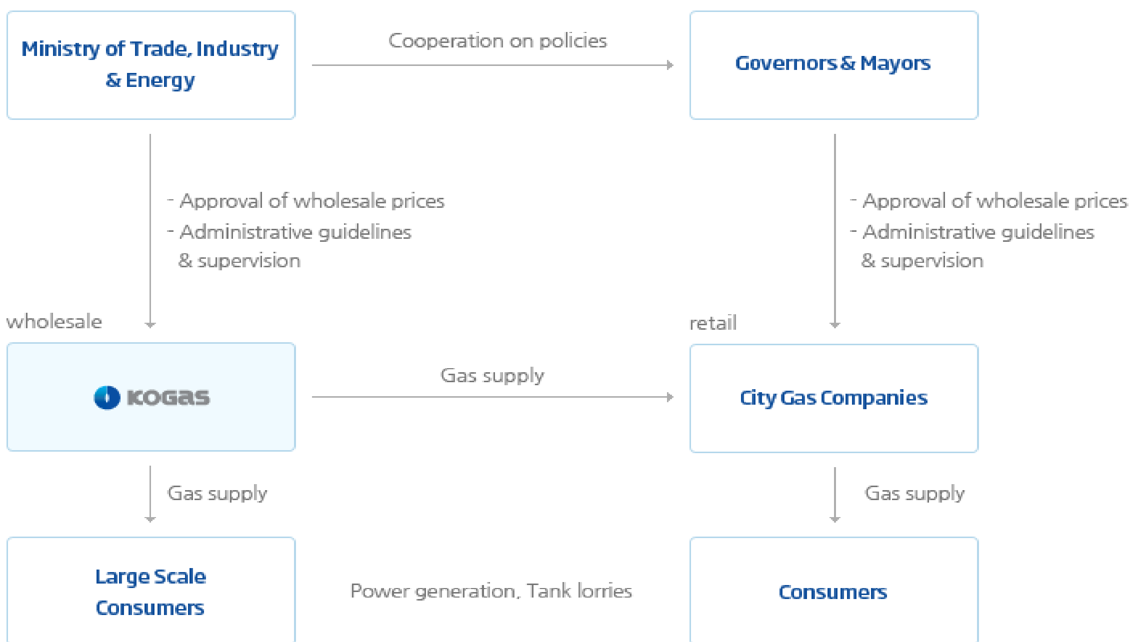


Figure 14: Korea's Natural Gas Business Flow Chart (KOGAS, undated b)

2.2.3. Coal

Korea's coal consumption has increased 4.3-fold between 1981 and 2015, mainly due to the increasing demand in the power-generation sector. Until 1989, more than half of the coals were used for residential and commercial purposes, mostly anthracite produced in domestic coal mines. About 47% of Korea's coal consumption in 1989 came from imported bituminous coal, mainly used in the iron and steel and cement industries. However, the shares of residential and commercial uses of coals have decreased significantly after the 1990s, and the power-generation and industrial sectors have replaced them. In 2015, Korea consumed 125.9 million tonnes of coals, among which 61% were used for power generation, 29.2% for iron and steel making, 5.6% for cement and other industries, and only 1.2% for the residential and commercial sectors (Figure 15).

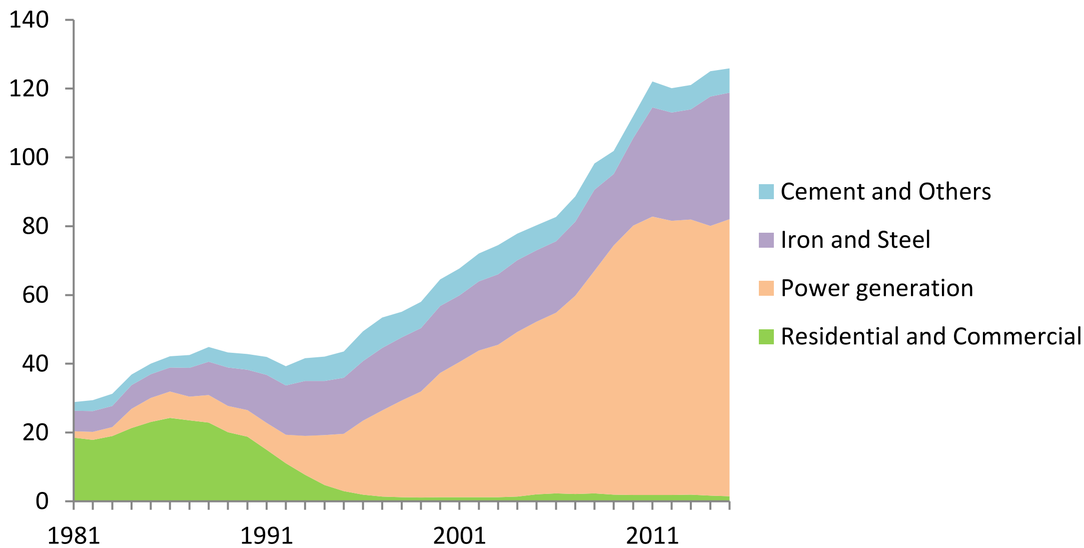


Figure 15: Korea's Coal Consumption by Sector (million tonnes) (KEEI, 2017b)

Korea has no bituminous coal mines and most of the coal products are anthracites. In 1981, Korea produced 19.9 million tonnes of anthracites, which were a main energy source for residential heating and cooking until the 1980s. However, the consumption of anthracites has declined rapidly in the 1990s as oil, gas, and electricity replaced them. Moreover, the Korean government began to remove subsidies in the late 1980s. As a result, the domestic anthracite production decreased to 1.8 million tonnes in 2015, which was just 1.4% of Korea's total coal consumption (Figure 16). The number of operating coal mines in Korea has decreased from 361 in 1986 to only 5 in 2015 (MIRECO, 2010, 2016).

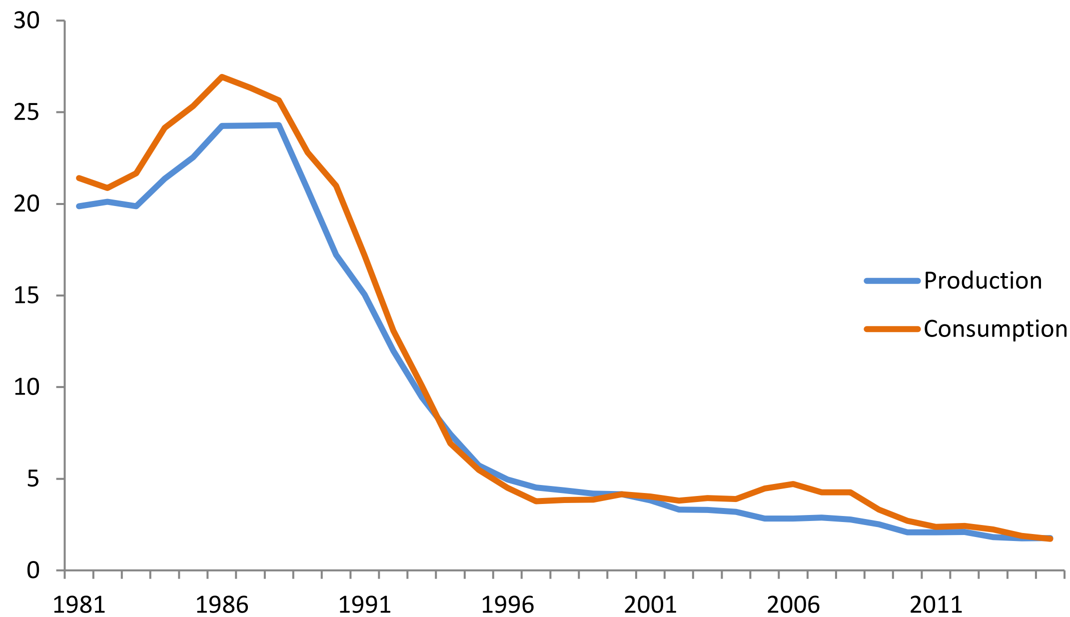


Figure 16: Korea's Coal (Anthracite) Production and Consumption (million tonnes) (KEEI, 2017b)

On the other hand, the consumption of bituminous coals has increased substantially over the last few decades, driven by growing demand in Korea's power-generation and industrial sectors (primarily steel and cement). Most of the bituminous coals came from abroad, and Korea's coal imports have risen 10-fold between 1981 and 2015 (Figure 17). As a result, Korea became the world's 4th largest coal importer in 2015, following China, India, and Japan. Australia accounted for 45% of Korea's coal imports, Indonesia 25%, Russia 17%, and Canada 7% in 2015 (US EIA, 2017).

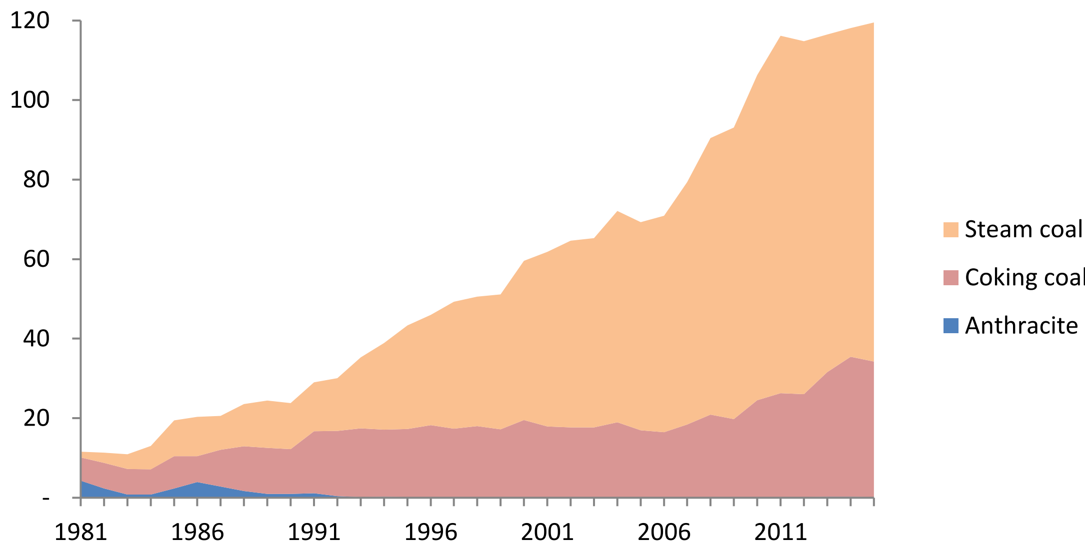


Figure 17: Korea's Coal Imports by Type (million tonnes) (KEEI, 2017b)

2.2.4. Electricity

In 2015, Korea consumed 483.7 terawatt hours (TWh) of electricity, equal to about 20% of Korea's final energy consumption. Industries accounted for 54.9% of total electricity consumption, the commercial sector 26.8%, the residential sector 13.2%, and the public sector 5%. Between 1981 and 2015, Korea's total electricity consumption has increased about 14-fold, and the electricity consumption per capita has risen 10-fold (Figure 18). As a result, Korea became the 8th largest electricity consumer in the world (Enerdata, undated). Recently, the growth rate of electricity consumption has slowed due to Korea's low economic growth, warm climate, and demand-side management. Korea's electricity consumption per capita was 9,305 kWh in 2014, which was above both the world average (3,030kWh) and the OECD average (8,028kWh). This is mainly because of high electricity consumption in industrial sectors such as the metal, petrochemical, electronics, and automobile industries (KEEI, 2017b).

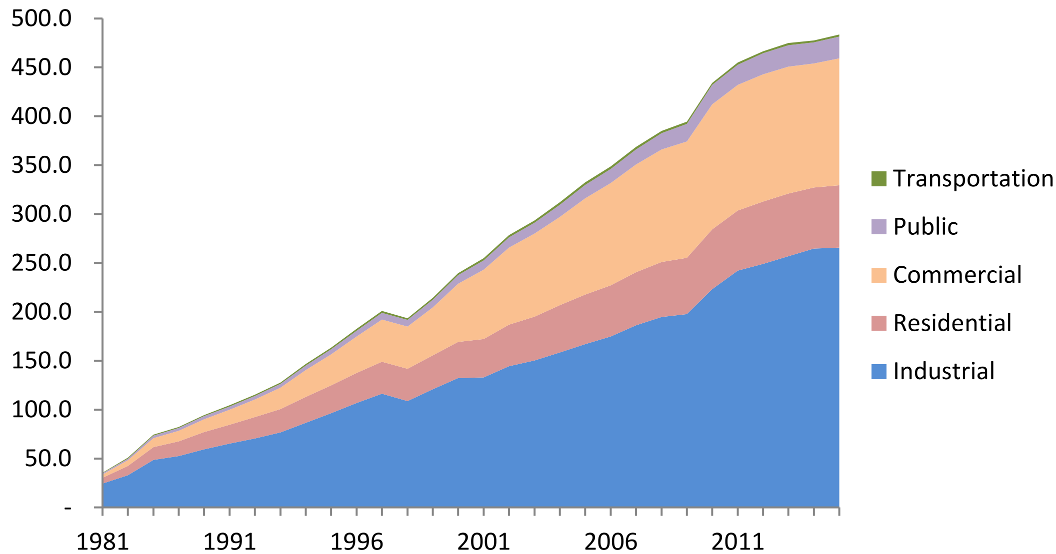


Figure 18: Korea's Electricity Consumption by Sector (TWh) (KEEI, 2017b)

In 2015, Korea generated 528.1 TWh of electricity exclusive of non-utility generation. Fossil fuels accounted for about 63.7% of total power generation, 31.2% came from nuclear power, and 5.1% from renewable sources, including hydro-electricity. Nuclear and coal have been the dominant power sources in Korea for several decades. Nuclear and coal-fired power have provided more than half of Korea's total power generation since 1985, and they have provided about 70.1% of total electricity between 1981 and 2015. LNG started to be used for power generation in the mid-1980s and has become a main source for electricity, accounting for 19.1% of total power generation in 2015. Recently, the proportion of renewables has grown rapidly from 1.5% in 2005 to 5.1% in 2015 (Figure 19).

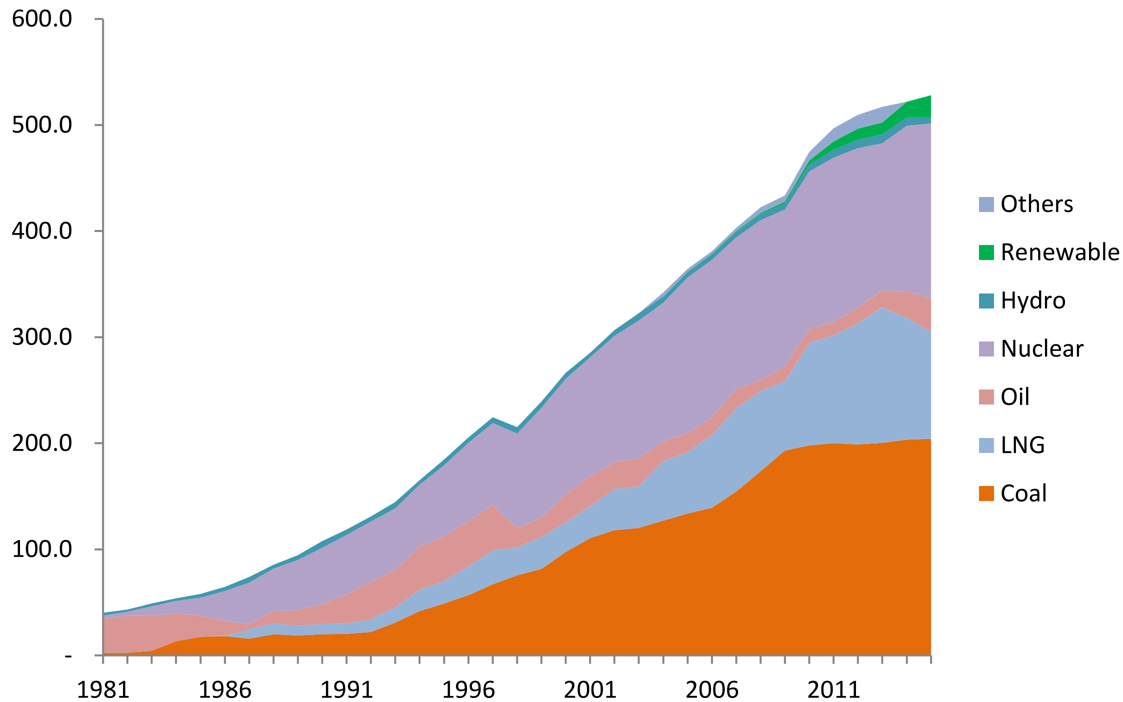


Figure 19: Korea's Power Generation by Source (TWh) (KEEI, 2017b)

In 2015, Korea's generating capacity was 97.6 gigawatts (GW), consisting of natural gas combined cycle (29.2%), coal-fired (26.9%), nuclear (22.2%), hydro-electric (6.6%), and renewable energy (5.8%) power plants (Figure 20). Korea's base load generation is mainly made up of coal and nuclear power, whereas peak demand is generally met by natural gas (US EIA, 2017). In 2015, the capacity factors of coal-fired and nuclear power plants were 90.1% and 85.3%, respectively. These were high above the average capacity factor (61.6%) of all power plants. In contrast, the capacity factor of the natural gas combined cycle was just 40.3% in the same year (KEPCO, 2016).

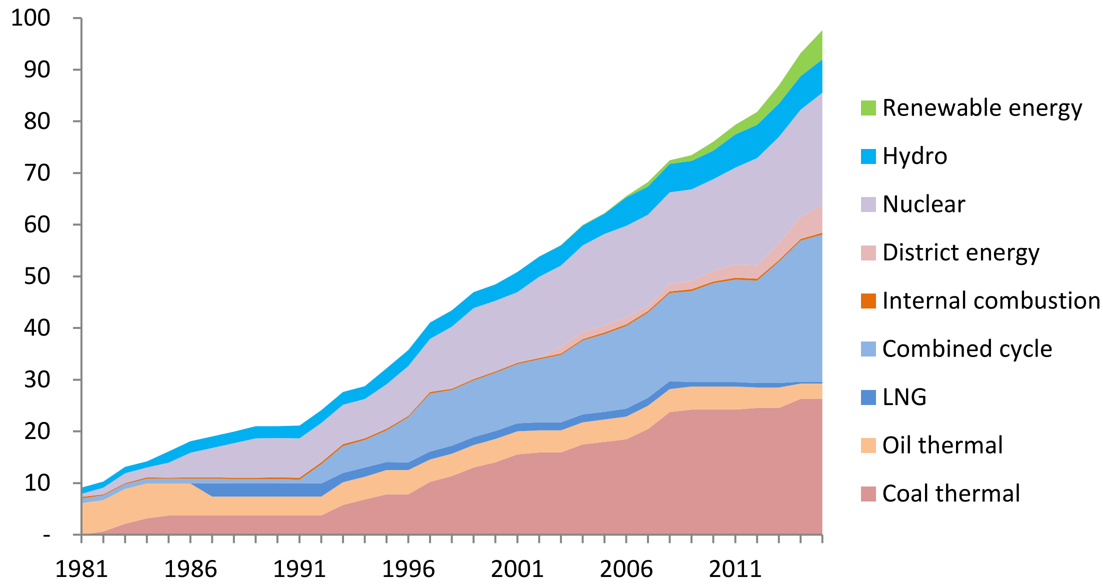


Figure 20: Korea's Power Generating Facilities (GW) (KEEI, 2017b)

Between 1981 and 2015, Korea's generating capacity has increased with an average annual growth rate of 7%, driven by the rapidly increasing demand for electricity. Recently, the growth rate has slowed down, falling to 3.6% in 2010. However, this rebounded after the limited blackout in 2011, which was caused by a sudden increase in electricity demand in the summer. The average increasing rate of generating capacity between 2012 and 2015 was 5.3%. Around 47.6% of installed power plants in this period were natural gas combined cycle, and 20.7% were renewable energy power plants (KEEI, 2017b). Given the recent slowing down demand for electricity and the rapid expansion of power plants, overcapacity in the electricity market in Korea is expected to continue for a while.

For several decades, Korea Electric Power Corporation (KEPCO) has controlled all aspects of electricity, including generation, transmission, distribution, and retail sales in Korea. However, in 2001, KEPCO's generation assets were spun off into six separate subsidiary power generation companies, including Korea Hydro & Nuclear Power Corporation, by reform of the electricity sector by the government to promote competition in the electricity market. Although the initial restructuring included plans to divest KEPCO of the generation sector, KEPCO still owns shares of the subsidiary generation companies and related companies such as KEPCO Engineering and Construction, KEPCO Nuclear Fuel, and KEPCO Knowledge Data Network (KEPCO, undated a).

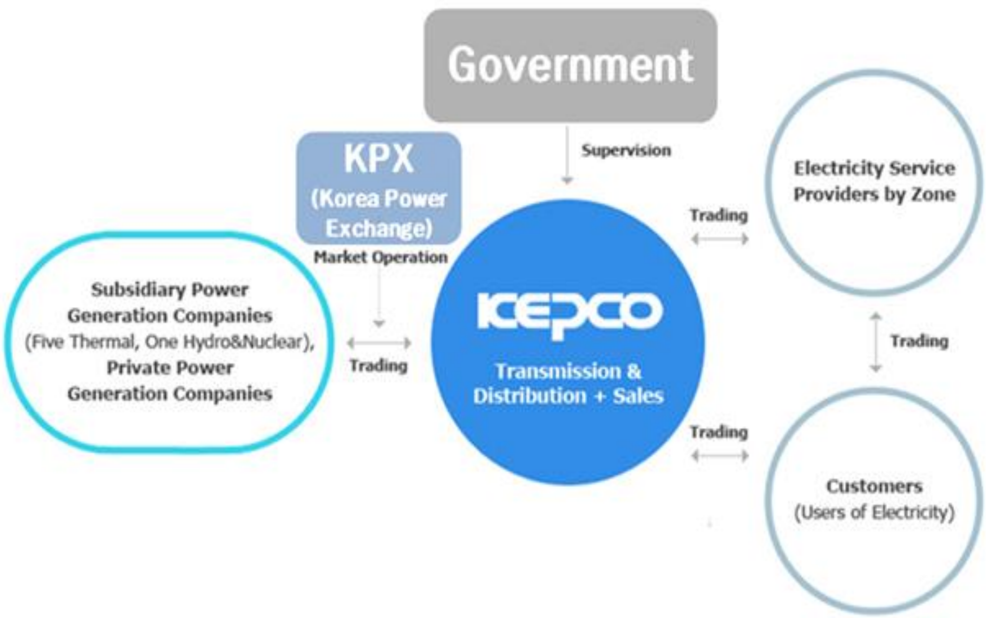


Figure 21: Korea’s Electricity Market Structure (KEPCO, undated b)

In Korea, KEPCO’s six subsidiary power-generation companies, independent power producers, and community energy systems are producing the country’s electricity. In 2015, KEPCO’s subsidiary companies accounted for 80% of total power generation and independent power companies for 18%. Korea Power Exchange (KPX), established in

2001, serves as a system operator and coordinates the wholesale electricity market. KPX regulates the cost-based bidding-pool market and determines prices sold between electricity generators and the KEPCO grid (KPX, undated). KEPCO purchases electricity from KPX, transports it through the transmission and distribution network, and sells it to general customers (KEPCO, undated b).

2.2.5. Renewable Energy

In Korea, “new and renewable energy (NRE)” comprises new energy and renewable energy sources. It is a little bit different from the general concept of renewable energy. New energy means unconventional, high-tech energy sources including hydrogen, fuel cells, CTL (Coal to Liquid), and IGCC (Integrated Gasification Combined Cycle), which are usually not included as renewable energy in other countries. Renewable energy consists of solar, wind, hydro power, biomass, geothermal, marine, and waste energy. However, in Korea, conventional large scale hydro-electric power is not included in renewable energy statistics, and the range of waste energy is different from that of the International Energy Agency (IEA) (Yoon and Sim, 2015). These differences should be considered in using Korea’s renewable energy statistics. From now on, hydro-electric power will be included in Korea’s renewable energy statistics, but new energy will not be included. However, waste energy statistics will be used unchanged.

In 2015, Korea’s renewable energy supply was 14.3 Mtoe, which was about 5% of Korea’s TPES. Waste, bio, and hydro contributed 90.2% of total renewable energy supply, and the shares of other types of energy sources were insignificant. Waste energy was the largest, accounting for 59.1% of total renewable energy supply. Bio energy was the second

(19.4%), followed by hydro (11.7%), solar PV (5.9%), and wind (2.0%). Between 2004 and 2015, Korea's renewable energy supply increased by 8.1% annually, which was far above the growth rate of TPES (2.5%). The average annual growth rates of solar PV, wind, bio, and geothermal were higher than 30%, whereas waste energy has increased by only 8.9% annually. Hydro and solar thermal energy supply has even decreased. As a result, the shares of solar PV, wind, and bio energy in Korea's total renewable energy supply have sharply increased recently (Figure 22).

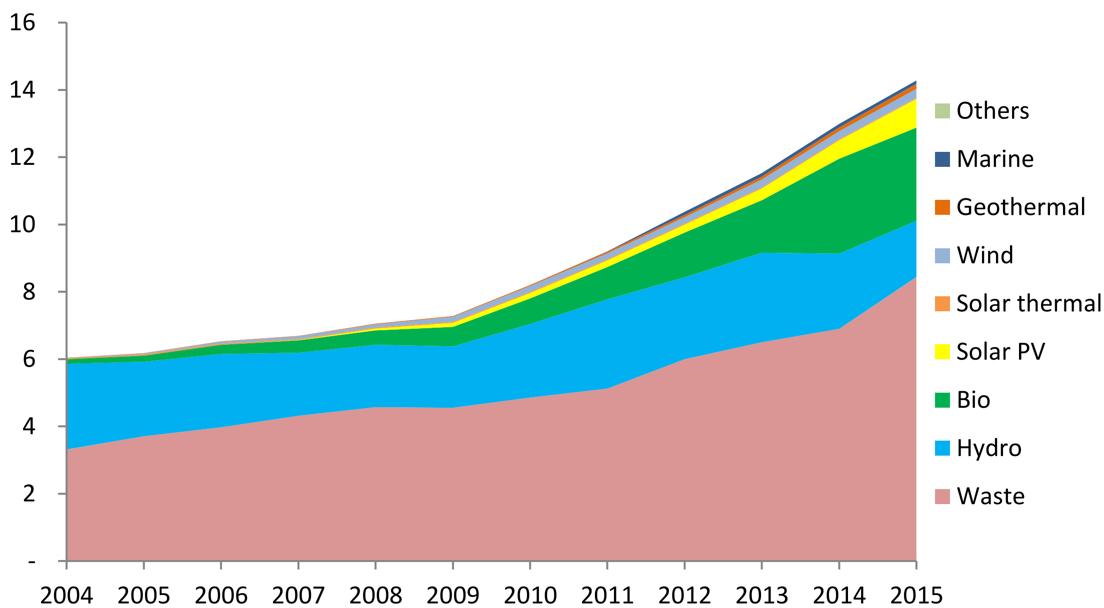


Figure 22: Korea's New and Renewable Energy Supply (Mtoe) (KEA, 2016)

Most of the renewable sources, such as solar PV, hydro, and wind were used for power generation. The electricity generated from renewable sources was 41.8 TWh in 2015, which was about 7.5% of total power generation of Korea. However, biodiesel, accounting for 16% of bio energy, was mainly used for cars by blending with petroleum-based diesel (KEEI, 2017b). Other bio energy and waste energy were used for various purposes such as power generation, industrial production, and residential heating (KEEI, 2017b).

There are now more than 400 renewable energy companies in Korea. This number has increased sharply after the launch of RPS (Renewable Portfolio Standard) in 2012. According to the Korea Energy Agency (KEA), the total revenue from the renewable energy industry was about US $10 billion in 2015, and US $700 million was invested in the same year. The number of employees working in this industry was more than 15,000 (KEA, 2016). However, Korea's renewable energy industry is still in its early stage, and it lacks price competitiveness compared to fossil fuels. As a result, the renewable industry depends highly on government policies and subsidies.

The Korean government has tried to promote the renewable energy industry by various policy tools. It is making a basic plan for new and renewable energy (NRE) every 5 years. These plans suggest policy directions for renewable energy. According to the 4th basic plan in 2014, the supply target for NRE was to increase the share of new and renewable energy supply to 11% of TPES by 2035 (Table 2). It plans to develop solar and wind power as main sources of energy while reducing the relative importance of waste energy, so that 13.4% of total electricity is supplied by NRE by 2035. The Korean government also focuses on transforming the NRE market fundamentally, from a government-led system to a privately driven partnership (MOTIE, 2014b).

	2012	**2014**	**2020**	**2025**	**2030**	**2035**
NRE Supply Target	3.2%	3.6%	5.0%	7.7%	9.7%	11.0%

Table 2: Korea's NRE Supply Target (% of NRE in TPES; MOTIE, 2014b)

The feed-in tariff was one of the major policies to promote new and renewable energy in Korea. The Korean government guaranteed fixed rates for electricity generated from renewable sources and compensated eligible renewable energy generators for the differences between the system marginal price (SMP) and the fixed rate for electricity. This program was implemented from 2001 to 2011 and was replaced by a RPS (Renewable Portfolio Standard) in 2012 (IEA, 2008). RPS has placed an obligation to power suppliers with a capacity of more than 500 MW to produce a certain amount of electricity from new and renewable sources. The level of obligation targeted in 2015 was 3% of the total power generation, which is planned to increase to 10% by 2024 (Table 3).

	2015	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**
RPS Target	3.0%	3.5%	4.0%	4.5%	5.0%	6.0%	7.0%	8.0%	9.0%	10.0%

Table 3: Korea's RPS Target (% of NRE in total power generation) (MOTIE, 2014b)

Besides the RPS, the Korean government provides subsidies for the installation of renewable energy facilities in residential areas, buildings, and local provinces to accelerate renewable energy deployment. It also provides long-term and low-interest loans for the installation of renewable energy facilities. Public buildings having more than 1,000m^2 of floor space were required to generate more than 12% of total energy use by new and renewable resources in 2012, which rises to 30% in 2020. A RFS (Renewable Fuel Standard) was implemented in 2015 that mandates oil refiners, oil importers, and exporters to blend certain amount of bio-fuels into transportation fuels. At present RFS is only applied to biodiesel mixed with petroleum-based diesel. Bio-ethanol and biogas are expected to be further reviewed depending on the market conditions (KEA, 2015).

3. ESTIMATION OF USEFUL WORK OF KOREA

3.1. DEFINITION

3.1.1. Exergy

The exact definition of "energy" is different from the meaning of energy that we use in our daily lives. Energy is conserved in all transformation processes according to the first-law of thermodynamics. It is only degraded from available to less available forms. (Dincer and Rosen, 2012). Energy content does not reflect the quality of energy, and not all energy can perform useful work. For example, the ocean has a tremendous amount of heat energy, but that energy cannot be converted into useful work if there is no temperature gradient with its surroundings (Ayres and Warr, 2005).

However, the term "exergy" reflects both the quality of energy and its potential to do useful work. Exergy means a maximum amount of work that could be done by an energy source as it becomes in thermodynamic equilibrium with its reference environment. For instance, the heat of boiling water can do work until its temperature becomes equal to the surrounding air temperature. Unlike energy, exergy is destroyed in most of the conversion processes that perform useful work, resulting in the increase of entropy. So, exergy is the concept that most people think of when considering energy (Dincer and Rosen, 2012).

A unit of exergy is same as an energy unit, but the exergy value may be smaller or larger than the energy content. The exergy values of work and electricity are equal to their energy contents, but the exergy value of heat flow is usually less than its energy content. Since the actual works and services that energy provides are important for economic activities, exergy could be a good measure to use in clarifying the role of energy in economic growth (Ayres, 2008). However, we need more to evaluate the relationship between them. Since exergy is a theoretical maximum work potential in an ideal process, it is usually different from the work actually done. Thermodynamic second-law efficiency (exergy efficiency) plays an essential role between them (Ayres and Warr, 2005).

3.1.2. Exergy Efficiency

In thermodynamics, energy efficiency (first-law efficiency) and exergy efficiency (second-law efficiency) are generally used to measure the efficiency of energy uses. Energy efficiency is the ratio of desired energy output to energy input (Dincer and Rosen, 2012). For example, the energy efficiency of a gasoline engine in a car can be defined as the ratio of mechanical work output to energy content of consumed gasoline. In this case, energy efficiency is between 0 and 1. However, energy efficiency could be greater than 1 in some cases. For instance, the energy efficiency of a heat pump can be greater than 1 due to the heat input from the environment (Serrenho et al, 2015). So, it could be inappropriate to compare the efficiencies of different energy-using processes in terms of their energy efficiency.

In contrast, exergy efficiency is defined as the ratio of desired exergy output to exergy input. It should be between 0 and 1 since exergy is always destroyed in conversion processes according to the second-law of thermodynamics. Exergy efficiency compares the actual amount of desired work output with the theoretical maximum work output. Because of the destroyed exergy (or increased entropy) during a process, exergy efficiency cannot be greater than 1. In short, exergy efficiency measures the closeness of an actual process to its ideal process for a given energy use. Therefore, the exergy efficiency gives a better understanding of performance than does energy efficiency (Dincer and Rosen, 2012).

3.1.3. Useful Work

Useful work is an amount of exergy actually used at the end-use stage. Mechanical work of a car generated from gasoline, heat used for residential heating, or light emitted from a bulb are examples of useful work. Useful work is always less than the exergy value because, in reality, there is no system with 100% exergy efficiency. This means that the amount of exergy actually used for final end-use is less than the original exergy input. Therefore, the useful work of a country is a good measure for the actual services that energy provides for an economy, and it enables better insights into the role of energy in economic growth. It is calculated by multiplying exergy values of energy sources consumed at the end-use stage by its exergy efficiency. The units of exergy and energy are also used for useful work (Serrenho et al., 2014).

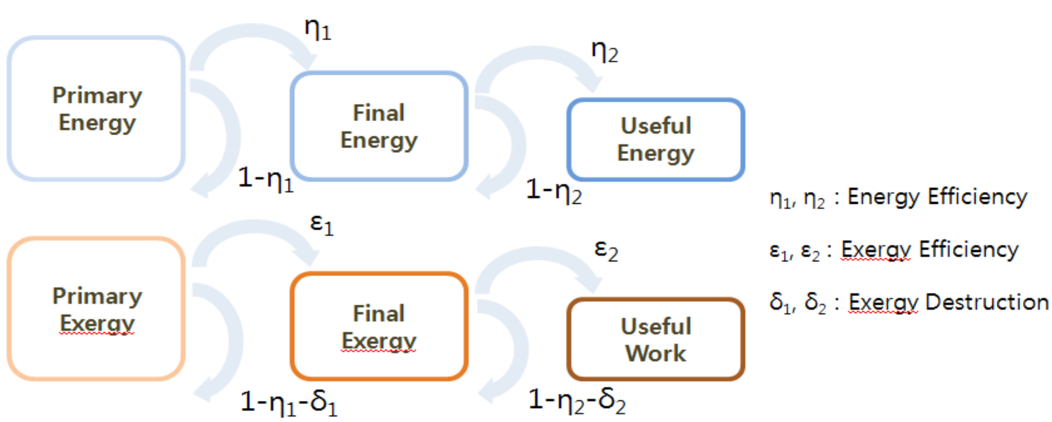


Figure 23: Energy and Exergy Flows (Serrenho et al., 2014)

3.2. METHODOLOGY AND DATA

3.2.1. Overall Processes

Useful work (U_{ijt}) of each end-use category (i), energy carrier (j), for each year (t) can be calculated by using final energy consumption data (E_{ijt}), exergy factor of each energy source (α_j), exergy efficiency (ε_{ijt}) of each end-use categories for the entire period of the analysis. Total useful work consumption of a country for each year can be obtained by summing all useful works of end-use categories (Serrenho et al., 2014).

$$U_{ijt} = E_{ijt} \cdot \alpha_j \cdot \varepsilon_{ijt} \tag{1a}$$

$$U_t = \sum_i \sum_j U_{ijt} \tag{1b}$$

This process requires calculating exergy value using the exergy factor of each energy source, reallocating final energy consumption data into useful work categories, and estimating exergy efficiency of each end-use category. There are various energy databases for final energy consumption data, but the International Energy Agency (IEA) and Food and Agriculture Organization of the United Nations (FAO) provide energy and food consumption data that have an adequate level of disaggregation. Serrenho et al. (2014) suggested a systematic approach to estimate national level useful work consumption using IEA's World Energy Statistics data and FAO's Food Balance Sheet. Useful work consumption of Korea can be calculated by using the same methodology, applied step by step, as shown below.

1. Unifying units of various energy sources in final energy consumption data
2. Converting energy contents in final energy consumption data to exergy values
3. Mapping exergy values of each end-use sector to useful work categories
4. Estimating exergy efficiency of each useful work category
5. Calculating useful work from food consumption data
6. Obtaining total useful work by summing the useful works of all categories

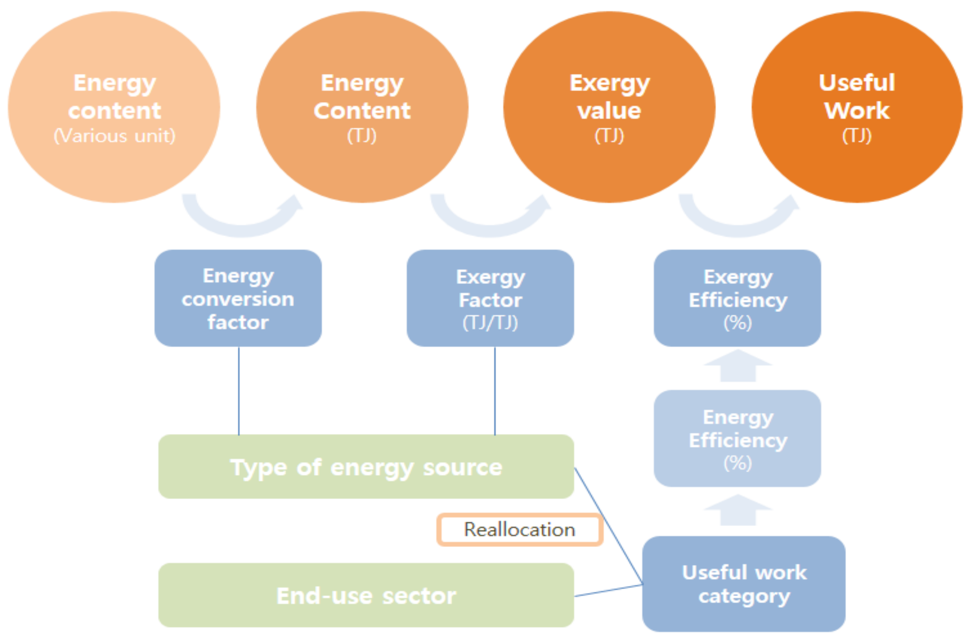


Figure 24: Overall Process for Calculating Useful Work (Serrenho et al., 2014

3.2.2. Unifying the Units of Energy Sources

In the IEA database, the "energy industry own use" and "final energy consumption" data for Korea are required for calculating useful work used for economic activities, but non-energy use data should be excluded. IEA's World Energy Statistics provides Korea's energy consumption data from 1973 to 2014, categorized by end-use sectors and energy carriers. Since these data are provided by the energy carrier's own unit (kg, TJ, GWh, etc.), they have to be converted to unified unit such as joule, calorie, or toe (Table 4). Furthermore, IEA energy statistics use both gross calorific value (GCV) and net calorific value (NCV) according to the characteristics of energy carriers. The difference between them arises from water vapors in energy sources, and GCV is larger than NCV.

Product	**Hard coal (kt)**	**Anthracite (kt)**	**Coking coal (kt)**	**...**	**Electricity (GWh)**	**Heat (TJ)**
Energy industry own use	0	0	0	...	39782	4591
Coal mines (energy)	0	0	0	...	0	0
Oil and gas extraction (energy)	0	0	0	...	0	0
...	...	...	...	...	...	...
Final energy consumption	0	2149	1455	...	486834	190845
Industry	0	2149	1455	...	259606	10577
Iron and steel	0	1819	1455	...	55426	1187
...	...	...	...	...	...	...

Table 4: Example of IEA's Energy Statistics Data (IEA, 2016)

In this analysis, tera joule (TJ) and gross calorific value (GCV) will be used since some IEA data use TJ, and GCV is closer to the concept of exergy. Different energy sources can be unified in TJ by multiplying energy conversion factors based on GCV. Most of the energy conversion factors were obtained from IEA's 'Energy Statistics Manual (IEA, 2005)', 'Unit of Measurement and Conversion Factors (IEA, 2008)', and other conversion factors for some of petroleum and renewable products were obtained from Energy Statistics document of the the United Nations (UN, 1987) (Appendix A: Table 1).

3.2.3. Converting Energy Contents to Exergy Values

The exergy value of an energy source is the ability to perform work, which in turn depends on its energy content, the properties of the energy source, and the surrounding environment (Dincer and Rosen, 2012). For example, the exergy values of heat flow and electricity with the same energy contents are different. Exergy value of a heat flow varies according to the environment temperature, and it is usually less than its energy content. A general exergy factor is a convenient tool with which to convert energy contents of various energy sources to exergy values.

The exergy value is defined by the ratio of exergy value to energy content of each energy source. Since mechanical work is exergy itself by definition, and electricity can be completely transformed into work, each has an exergy factor of 1. However, heat cannot be completely converted to work. So, the exergy value of heat flow is less than 1 and is even zero when there is no temperature gradient with its environment. The exergy values of chemical energy sources including fossil fuels depend on their chemical potential to do work during combustion (Klein and Nellis, 2011) (Table 5).

Energy sources	Exergy value	
Work	$A = W$	Available work is exergy by definition
Electricity	$A = E$	Electricity can be completely converted to work
Heat	$A = E(1-T_0/T_h)$	Work can be done by a Carnot cycle working between T_h and T_0
Fuel	$A = \|\Delta H\| - T_0\Delta S \fallingdotseq \|\Delta H\|$	Exergy of fuel is chemical work of its combustion

* A = Exergy, W = work, E = Energy content, T_h: temperature of heat flow, T_0: environment temperature, $|\Delta H|$: heat of combustion, $T_0\Delta S$: heat rejected as a consequence of the entropy received

Table 5: Exergy Values of Different Energy Sources (Serrenho et al., 2016)

The energy content of each energy source can be converted to an exergy value by multiplying by its exergy factor. Serrenho et al. (2014) summarized the exergy factors for several energy sources that can also be used in this analysis. However, the exergy factor for the heat category has to be calculated by considering the temperatures of heat flow and its environment. In this analysis, the average temperature of Seoul between 1973 and 2014 was used for the reference environment temperature (Korea Meteorological Administration, undated) and 180℃ was assumed as the temperature of heat flows provided in all economic sectors (Serrenho et al., 2015) (Table 6).

Energy sources	**Exergy factors**	
Coal products	1.06	
Oil products	1.06	
Coke	1.05	
Natural gas	1.04	
Combustible renewables	1.11	
Electricity	1.00	
Food	1.00	
Heat*	0.39	Exergy factor (heat) = 1 - (12.4 + 273) / (180 + 273)

* Assumption: T_0 = 12.4℃ (Average annual temperature of Seoul between1973 and 2014)
T_h = 180℃ (Temperature of heat flows provided for end-uses in all economic sectors)

Table 6: Exergy Factor of Each Energy Carrier (Serrenho et al., 2014)

3.2.4. Allocating Exergy Values to Useful Work Categories

Useful work is calculated by multiplying exergy values by its exergy efficiency. The IEA World Energy Statistics provides final energy consumption data classified by economic sector and energy source, and the exergy value of each category can be easily calculated by using exergy factors. However, it is almost impossible to estimate exergy efficiencies of all categories divided by various economic sectors and energy carriers. As a result, exergy values obtained from final exergy consumption data have to be reallocated to useful work categories (heat, mechanical drive, light, and other electric uses) in which exergy efficiencies for the analysis period can be estimated (Table 7). A full set of mapping criteria for useful work categories is suggested in the Appendix (Appendix A: Table 2).

Useful work category	**Sub-category**	**Abbreviation**
Heat	Fuel – High temperature heat (500ºC)	H
	Fuel – Medium temperature heat (150ºC)	M
	Fuel – Low temperature heat (120ºC)	L(120)
	Fuel – Low temperature heat (90ºC)	L(90)
	Fuel – Low temperature heat (50ºC)	L(50)
	CHP – Medium temperature heat (150ºC)	CHP-M
	CHP – Low temperature heat (120ºC)	CHP-L(120)
	CHP – Low temperature heat (90ºC)	CHP-L(90)
	CHP – Low temperature heat (50ºC)	CHP-L(50)
	Electricity - Medium temperature heat (150ºC)	EH
Mechanical drive	Coal – Stationary mechanical drive	CM
	Oil – Stationary mechanical drive	OM
	Steam locomotives	SL
	Diesel vehicles	DV
	Gasoline/LPG vehicles	GV
	Natural gas vehicles	NV
	Aviation	A
	Navigation	N
	Diesel-electric	DE
	Electric mechanical drive	EM
Light	Coal/Oil light	CL
	Electricity light	EL
Other electric uses	Other electric uses	EO
Muscle work	Human muscle work	MW

Table 7: Useful Work Categories (Serrenho et al., 2014)

Heat category comprises all end-use sectors that use heat flows in devices or processes. Since exergy efficiency of this category strongly depends on the temperature of heat flow, heat category is subdivided into high temperature heat (higher than 500℃), medium temperature heat (between 120℃ and 500℃), and low temperature heat (between 90℃ and 120℃, between 50℃ and 90℃, below 50℃). The high temperature heat flow is used in the iron and steel industry, in glass making, and in petroleum refining. The medium temperature heat is used for most industrial sectors, and the low temperature heat is used for hot water, cooking, and space heating (Serrenho et al., 2016).

The mechanical drive category includes processes that convert energy sources to physical work and use it as a final services of energy. Since exergy efficiencies are different according to the energy sources and conversion processes, the mechanical drive category is classified into the subcategories of stationary mechanical drive, steam locomotives, vehicles, and aviation. The light category includes all kinds of lighting end-uses. In the past, lighting usually came from oil products and town gas derived from coal, but currently most lighting comes from electricity (Serrenho et al., 2016).

Unlike other energy sources, electricity should be treated separately because it is used for various end-uses. Electricity is used for heat, mechanical drive, light, and other electric uses. Since the IEA World Energy Statistics only provides total final electricity consumption data for each economic sector, they should be allocated to end-use categories according to the percentage of them. Serrenho et al. (2014) estimated the shares of each electricity end-use for 15 European countries from 1960 to 2009 (Appendix A: Table 3). The exergy values of each end-use of Korea's electricity consumption from 1973 to 2014 can be calculated by using this data after assuming that the shares of each end-use are constant after 2009.

3.2.5. Estimation of Exergy Efficiency

Exergy efficiency is the percentage of useful work produced from exergy consumption. It is necessary to estimate exergy efficiencies of each useful work category for calculating useful work. Serrenho et al. (2014) estimated the exergy efficiencies of useful work categories for 15 EU countries from 1963 to 2009. This data can be applied to Korea after a little adjustment. The exergy efficiencies of mechanical drive, light, other electricity, and muscle work categories can be used without adjusting. However, exergy efficiencies of heat categories have to be modified reflecting the difference in environment temperatures between Korea and EU countries. Moreover, in this analysis, the exergy efficiencies from 2010 to 2014 are assumed to be same as those in 2009 because it is difficult to get consistent data for this period (Appendix A: Table 4, Table 5).

3.2.5.1 Heat Category

Heat categories are end-use sectors that exploit heating services from electricity, fuel combustion processes, or CHP facilities. The exergy efficiencies (ε) of heat categories depend on energy efficiency (η), reference environment temperature (T_0), and end-use service temperature of heat flow (T_2). If heat flow is used as an input, the temperature of heat flows provided (T_1) should also be considered. The exergy efficiencies of heat categories by energy sources are estimated as follows (Table 8).

$$\text{Exergy efficiency } (\varepsilon) = \text{Exergy output } (A_2) \,/\, \text{Exergy input } (A_1) \tag{2a}$$

$$\text{Energy efficiency } (\eta) = \text{Energy output } (E_2) \,/\, \text{Energy input } (E_1) \tag{2b}$$

Source	Exergy efficiency	Notes
Fuels	$\varepsilon = A_2/A_1$ $= E_2 \cdot (1-T_0/T_2)/A_1$ $\fallingdotseq \eta \cdot (1-T_0/T_2)$	ε: Exergy Efficiency (second-law efficiency) η: Energy Efficiency (first-law efficiency) A_1 : Exergy value of energy source A_2 : Exergy value of heat flow finally used E_1 : Energy content of energy source E_2 : Energy content of heat flow finally used T_0: Reference environment temperature T_1: Temperature of heat flow provided T_2: Temperature of heat flow finally used
Heat	$\varepsilon = A_2/A_1$ $= E_2 \cdot (1-T_0/T_2)/(E_1 \cdot (1-T_0/T_1))$ $= \eta \cdot (1-T_0/T_2)/(1-T_0/T_1)$	
Electricity	$\varepsilon = A_2/A_1$ $= E_2 \cdot (1-T_0/T_2)/E_1$ $= \eta \cdot (1-T_0/T_2)$	

Table 8: Exergy Efficiencies of Heat Category by Source (Serrenho et al., 2016)

Energy efficiencies of heat categories reflect the evolution of heat end-use devices such as furnaces, boilers, and heat exchangers which are mainly used in industrial processes. Serrenho et al. (2014) estimated 15 EU countries' exergy efficiencies of heat categories classified by service temperatures of heat flows, using energy efficiencies data from previous studies. In that analysis, environment temperatures were set differently for each country, making the exergy efficiencies different for each country (Serrenho et al., 2014). Since the temperatures between Korea and EU countries are different, the data should also be adjusted by applying Korea's average temperature data.

In this analysis, the average annual temperature of Seoul (the capital of Korea) from 1973 to 2014 was used as a reference environment temperature for heat categories that use heat services above 50℃. Assuming that most low temperature heat flows with service temperature of 50℃ were used for space heating in winter, the average winter (Dec-Feb) temperature of Seoul between 1973 and 2014 was applied in this category. For the heat category using electricity as an input, the energy efficiency was assumed to be 100%, and service temperature of heat flows finally used was assumed to be 120℃ for the industrial sector and 50℃ for the non-industrial sector (Table 9).

Useful work category	Service temperature	Reference temperature
Fuel – High temperature heat (500ºC)	500ºC	12.4ºC
Fuel – Medium temperature heat (150 ºC)	150ºC	12.4ºC
Fuel – Low temperature heat (120ºC)	120ºC	12.4ºC
Fuel – Low temperature heat (90ºC)	90ºC	12.4ºC
Fuel – Low temperature heat (50ºC)	50ºC	-0.81ºC
CHP – Medium temperature heat (150ºC)	150ºC	12.4ºC
CHP – Low temperature heat (120ºC)	120ºC	12.4ºC
CHP – Low temperature heat (90ºC)	90ºC	12.4ºC
CHP – Low temperature heat (50ºC)	50ºC	-0.81ºC
Electricity(Industry) - Low temperature heat (120ºC)	120ºC	12.4ºC
Electricity(Others) - Low temperature heat (50ºC)	50ºC	-0.81ºC

* Average annual temperature of Seoul from 1973 to 2014: 12.4℃
Average winter (Dec-Feb) temperature of Seoul between 1973 and 2014: - 0.81℃

Table 9: Reference Environment Temperature of Korea (Serrenho et al., 2014; KMA, undated)

3.2.5.2. Mechanical Drive Category

Mechanical drive categories comprise end-use sectors which use physical work derived from fossil fuels, bio-fuels, and electricity. Gasoline engine, diesel engine, steam locomotives, diesel-electric locomotives, aviation engines, and electric motors are equipment used in these sectors. The exergy efficiencies (ε) of mechanical drive categories using fuels and electricity is almost equal to the energy efficiency (η) since the work output is exergy itself by definition and exergy factors for these energy sources are close to 1. If energy source is heat flow, then exergy efficiency depends on the temperature of heat flow provided (T_1) and environment (T_0) (Serrenho et al., 2016). However, because the share of heat-using processes is negligible, the difference in temperature among countries will not be considered in this analysis (Table 10).

<table>
<tr><th>Sources</th><th>Exergy efficiency</th><th>Notes</th></tr>
<tr><td>Fuels</td><td>$\varepsilon = W_2/A_1$
$\fallingdotseq \eta$</td><td rowspan="3">ε : Exergy efficiency
η: Energy efficiency
A_1: Exergy value of energy source
W_2: Exergy value of work output
E_1: Energy content of energy source provided
T_1: Temperature of heat flow provided
T_0: Reference environment temperature</td></tr>
<tr><td>Heat</td><td>$\varepsilon = W_2/A_1$
$= W_2/E_1 \bullet (1-T_0/T_1)$
$= \eta/(1-T_0/T_1)$</td></tr>
<tr><td>Electricity</td><td>$\varepsilon = W_2/A_1$
$= \eta$</td></tr>
</table>

Table 10: Exergy Efficiency of Mechanical Drive Category (Serrenho et al., 2016)

3.2.5.3. Light and Other Electric Uses Categories

The light category includes usual lighting uses that came from oil, coal, and electricity. The lighting efficiency of each light source is usually defined by its luminous efficacy, which measures how well a light source produces visible light. Other electric uses category comprises electrochemical processes in industry and electric equipment used in homes, such as radios, TVs, refrigerators, heaters, and air conditioners. Serrenho et al. (2014) estimated the exergy efficiencies of these categories by using luminous efficacy data of the United Kingdom (Fouquet, 2008), exergy efficiency of communication and electronics and electrochemical end-uses of the U.S. (Ayres et al., 2005). The same data is applied for Korea after assuming that the exergy efficiencies of these categories are constant after 2009.

3.2.5.4. Muscle Work Category

The muscle work category comprises human work from food, but animal work from feed was not included because animal work is negligible in modern life. Calculating exergy values of food is based on country-level food supply data. The Food and Agriculture Organization of the United Nations (FAO) provides data on Korea's daily food supply per capita from 1973 to 2013. Since FAO's data is in metabolizable energy value, it should be converted to gross energy value (FAO, 2003; Wirsenius, 2000). The total exergy value of food supply in each year t (A_t) is calculated by multiplying daily food supply per capita (e_t) by 365 days, gross/metabolizable ratio (m), and population in the year (p_t) (Serrenho et al., 2016).

$$A_t = 365 \cdot e_t \cdot p_t \cdot m \tag{3a}$$

Because not all food supplied for human is eaten or used for physical work, more steps are required to obtain the values of useful work from food. Useful work in the muscle work category (U_t) is calculated by considering the exergy value of food (A_t), food intake ratio (r), working fraction of a day (h), and efficiency (ε), which are assumed to be constant regardless of time (Serrenho et al., 2014, 2016). Additionally, food supply per capita of Korea in 2014 is assumed to be same as in 2013 since there are no data for 2014 in FAO's database. The population of Korea from 1973 to 2014 was obtained from the Bank of Korea

(The Bank of Korea, 2017b). As a result, useful work from food is calculated as in Equation (3b) (Serrenho et al., 2016) (Table 11).

$$U_t = A_t \bullet r \bullet h \bullet \varepsilon = 365 \bullet e_t \bullet p_t \bullet m \bullet r \bullet h \bullet \varepsilon \tag{3b}$$

Variable	Estimate	Notes and references
U_t (useful work from food)	-	
e_t (daily food supply per capita)	-	Metaboilizable energy content of daily food supply per capita(FAO, 2017)
p_t (population in a year t)	-	Yearly population of Korea (The Bank of Korea, 2017b)
m (metabolizable / gross ratio)	1.16	Metabolizable/gross ratio for Asian countries (Wirsenius, 2000)
r (food intake ratio)	0.64	Ratio of eaten food to food supply (Wirsenius, 2000)
h (working fraction of a day)	1/3	Average hours of physical activity of a day: 8 hours
ε (efficiency)	0.13	Food to useful work efficiency (Smil, 1994)

Table 11: Variables in the Muscle Work Category (Serrenho et al., 2014)

3.2.6. Calculating Useful Work

Useful work is calculated by multiplying exergy value by exergy efficiency of each useful work category. Total useful work in a year t is obtained by summing the useful works of all categories. Calculated useful work consumption data of Korea from 1973 to 2014 are listed in Appendix (Appendix B: Table 1 - Table 3).

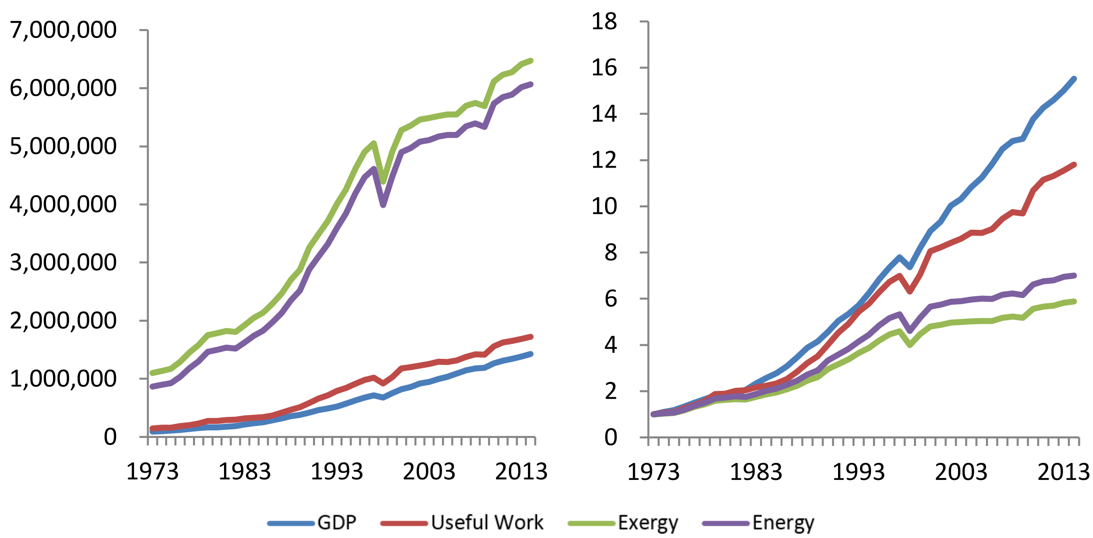
$$U_t = \sum_i U_{it} = \sum_i A_{it} \cdot \varepsilon_{it} \tag{4}$$

- U_t: total useful work consumption in a year t
- U_{it}: useful work consumption of useful work category i in a year t
- A_{it}: exergy consumption of useful work category i
- ε_{it}: exergy efficiency of useful work category i

4. Results

4.1. Useful Work Consumption

In 2014, Korea's useful work consumption was 1,723 peta joules (PJ) which was about 28.4% of final energy consumption. Between 1973 and 2014, Korea's useful work consumption has increased about 11.8-fold, with an average annual growth rate of 6.2%, whereas final energy consumption has grown 7-fold, with an average growth rate of 4.9%. Useful work consumption has increased faster than energy and exergy consumption, thanks to improvements in exergy efficiencies. During the same period, Korea's real GDP has grown 15.5-fold, 6.9% annually, which was closer to the growth rates of useful work than to rates of energy or exergy consumption (Figure 25).



< Real Value (TJ, 2010 billion Won) > < Standardized Value (1973 = 1) >

Figure 25: Korea's Useful Work, Exergy, Energy Consumption and GDP

The industrial sector has accounted for more than 60% of Korea's useful work consumption during Korea's economic development. The industrial sector still remains as a main driver for Korea's useful work consumption, and its share has increased from 60% in 1973 to 68% in 2014. The percentage of the commercial and public services sectors increased significantly after the 1980s, but it was only around 12% in 2014, and the transition to service economy has not been completed yet. The growth rate of useful work consumption of the transportation sector was the highest in the 1980s, and residential useful work consumption accelerated after the early 2000s. However, their growth has slowed in recent years, and the data suggest that useful work consumption of the residential and transportation sectors is saturated. Both of them accounted for about 10% of Korea's total useful consumption in 2014 (Figure 26).

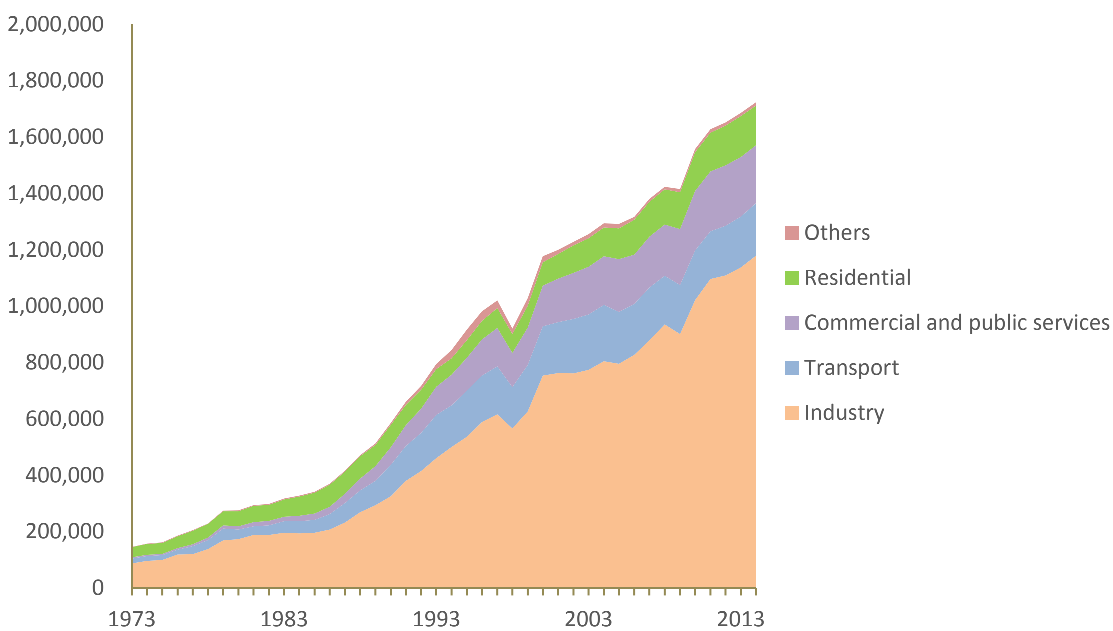


Figure 26: Korea's Useful Work Consumption by Sector (TJ)

Over the last few decades, the composition of useful work consumption has been closely related to the economic development of Korea. In the 1970s, low and medium temperature heat uses accounted for the majority of Korea's useful work consumption when industrialization was at its infant stage, and light industry remained high in Korea's economy. However, after the 1980s, high temperature heat and mechanical drive uses have gained importance as the development of heavy and chemical industry accelerated. The rapid increase of car uses in the 1990s also contributed to the increase in the mechanical drive uses. As a result, high temperature heat and mechanical drive uses accounted for 78.4% of Korea's useful work consumption in 2014. The shares of low and medium temperature heat uses were 7.5% and 20.1%, respectively, and other electric uses accounted for only 2.8%. Other types of useful work consumption, including light and muscle work uses, were negligible (Figure 27).

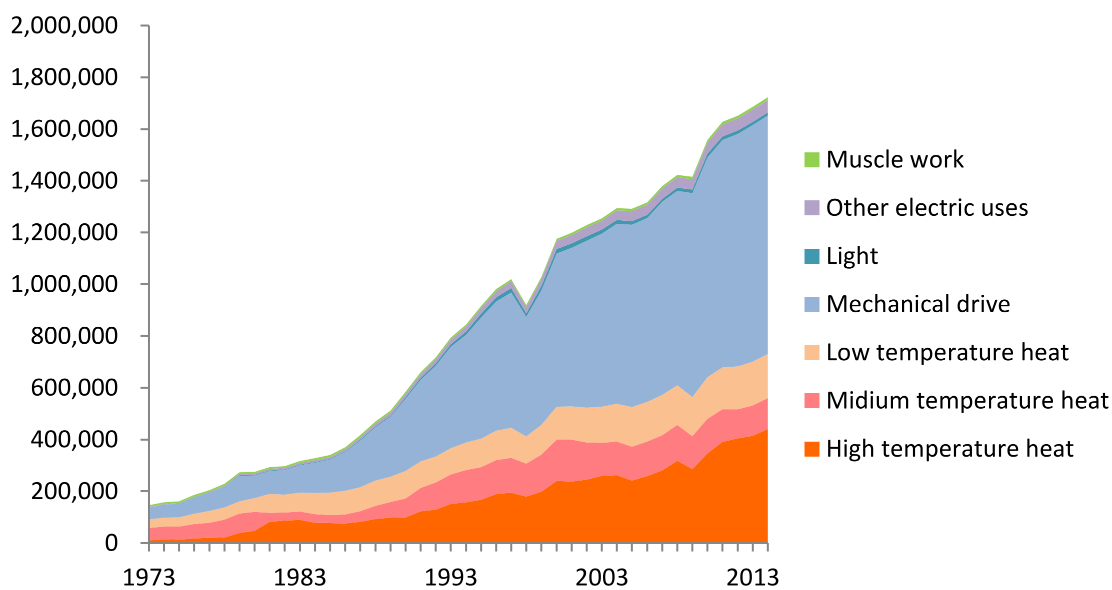


Figure 27: Korea's Useful Work Consumption by Useful Work Category (TJ)

4.2. Aggregate Exergy Efficiency

Korea's aggregate exergy efficiency can be calculated by dividing total useful work by total exergy consumption. It has increased from 13.3% in 1973 to 26.6% in 2014, which was much larger than the rates of the 15 EU countries estimated by Serrenho et al. (2014) (Figure 28). Even though energy efficiency data used for the 15 countries was also applied to Korea, the different composition of Korea's useful work consumption resulted in different results. Looking at the changes in the composition of Korea's useful work consumption over time, it seems that increasing use of high temperature heat and electric mechanical drive in industrial sectors greatly contributed to the rapid improvement of exergy efficiency because they have higher exergy efficiencies than do other types of useful work categories (Figure 27).

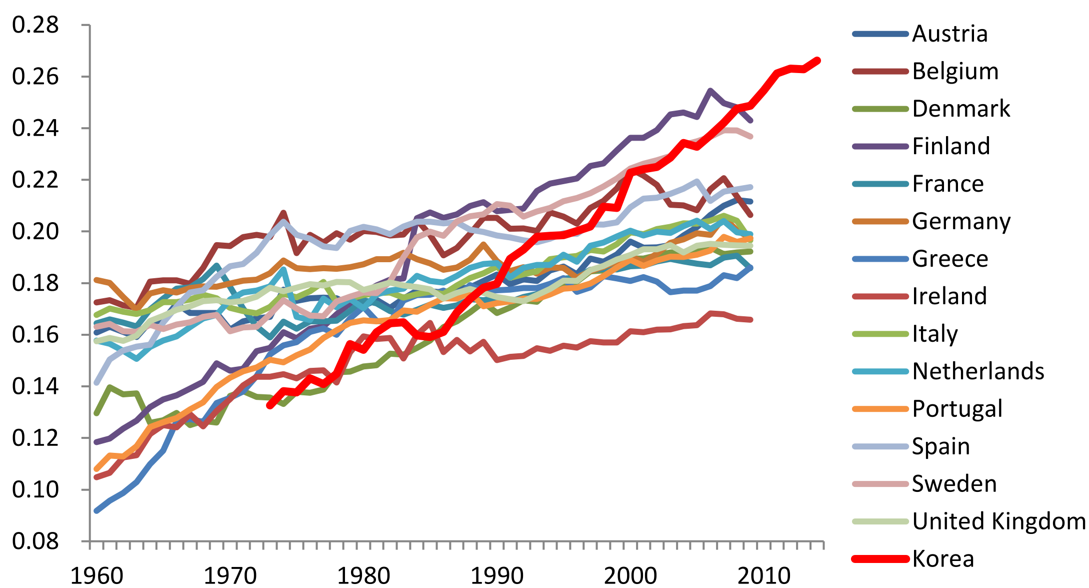


Figure 28: Exergy Efficiencies of Korea and 15 EU countries (Serrenho et al., 2014)

Considering that Korea’s compressed economic development has been achieved in a short period of time, this fast improvement in Korea’s aggregate exergy efficiency may not be strange. The transition from primary to secondary industry of the Korean economy after the 1960s and the changes of industrial structure from light to heavy and chemical industry after the 1970s would have also contributed to this rapid increase in exergy efficiency. In addition, since Korea's industrialization started later than that in the EU countries, Korea’s actual energy efficiency is expected to have increased more rapidly. So, Korea’s exergy efficiency could actually rise faster than is shown in Figure 28 if Korea’s actual energy efficiency data were used instead of EU data.

4.3. USEFUL WORK INTENSITY

Energy intensity is commonly defined as the ratio of energy consumption to the real GDP of a country. Depending on the stage of energy using processes, two different types of energy intensity could be measured. Primary energy intensity is the ratio of primary energy consumption to real GDP, and final energy intensity uses final energy instead of primary energy. These intensities have been widely used as a measure of productivity of energy uses or as an indicator for energy efficiency of a country (Serrenho et al., 2014). However, analyzing the relationship between energy and economy by these measures can lead to erroneous conclusion because they do not consider exergy efficiencies of end-use transformation processes and the actual services that energy provides. For example, the decline in energy intensities may be due not only to reduced energy consumption but also to improved exergy efficiency. As a result, unstable energy intensity cannot be a proof that energy consumption and economic growth are irrelevant (Serrenho et al., 2014).

Useful work intensity, the ratio of useful work consumption to real GDP, would be more appropriate than energy intensity for verifying the role of energy in an economy. Since useful work considers both quality of energy and exergy efficiency, it is better for measuring the overall efficiency of various energy uses in a national economic system and for verifying the relationship between energy and economic growth (Serrenho et al., 2014). The Bank of Korea provides Korea's real GDP series data from 1954 to 2015 in billion won, based on 2010, which can be used to calculate the useful work intensity of Korea (The Bank of Korea, 2017c).

Between 1973 and 2014, Korea's real GDP has increased 15.5-fold that was larger than the growth rates of useful work (11.8-fold), exergy (5.9-fold), and energy consumption (7-fold). As a result, all the intensities have decreased in this period and Korean economy became able to produce more goods and services with less energy inputs. Since useful work consumption has increased more rapidly than energy consumption, useful work intensity has been more stable than energy intensity, which could be an evidence for the close relationship between economic growth and useful work rather than that of energy consumption (Figure 29).

This is clearer when only the industry and services sectors are considered. Korea's useful work intensity has fluctuated between 1.2 TJ/B₩ and 1.7 TJ/B₩ from 1973 to 2014 and has shown a slightly decreasing trend, mainly due to the decreasing useful work intensity of the residential sector. Useful work intensity of the transportation sector has increased in the 1980s due to the rapidly increasing use of cars, but it has declined after the 1990s. Useful work intensities of the industry and services sectors have been relatively stable. As a result, useful work intensity, only including the industry and services sectors, has not shown a clear decreasing trend and has been stable near 1 TJ/B₩ (Figure 29, Figure 30).

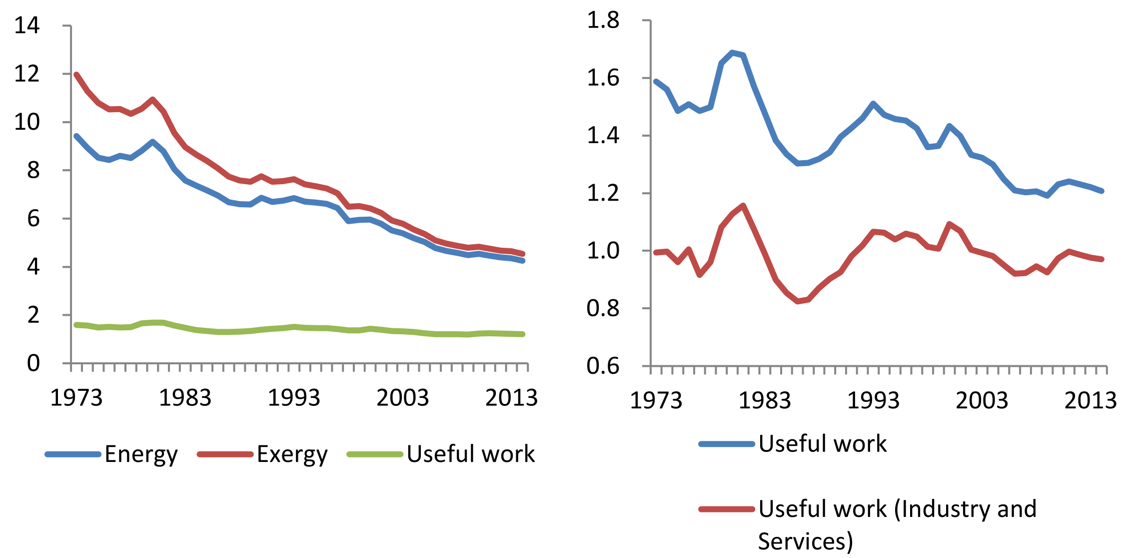


Figure 29: Energy, Exergy, and Useful Work Intensities of Korea (TJ/2010 B₩)

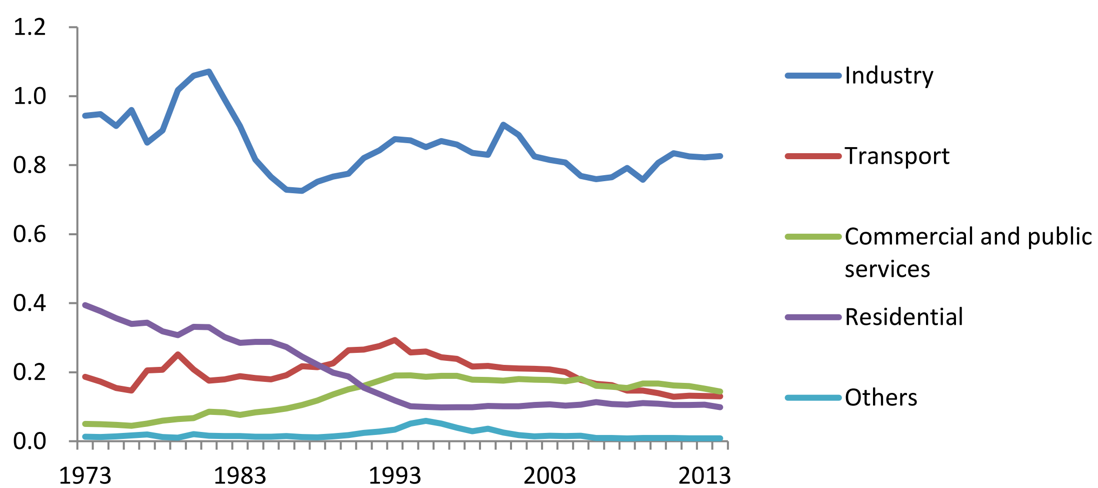


Figure 30: Korea's Useful Work Intensity by Sector (Useful Work of Each Sector / real GDP, TJ/2010 B₩)

The stability of the time series of Korea's useful work intensity, considering only industry and services sectors, near 1 TJ/2010 B₩, could be a more powerful indicator that useful work consumption of these sectors has more stable relationship to economic growth. It can be verified more clearly from the growth pattern of standardized real GDP and useful work consumption separated by sectors. According to Figure 31, Korea's useful work consumption, only including the industry and services sectors, has increased almost in line with real GDP growth, whereas the useful work consumption of the residential and transportation sectors has increased only slightly since the late 1990s. Considering the importance of industry in the Korean economy, and that Korea's transition to a service economy has not been finished yet, this relationship is expected to last for a while (Figure 31).

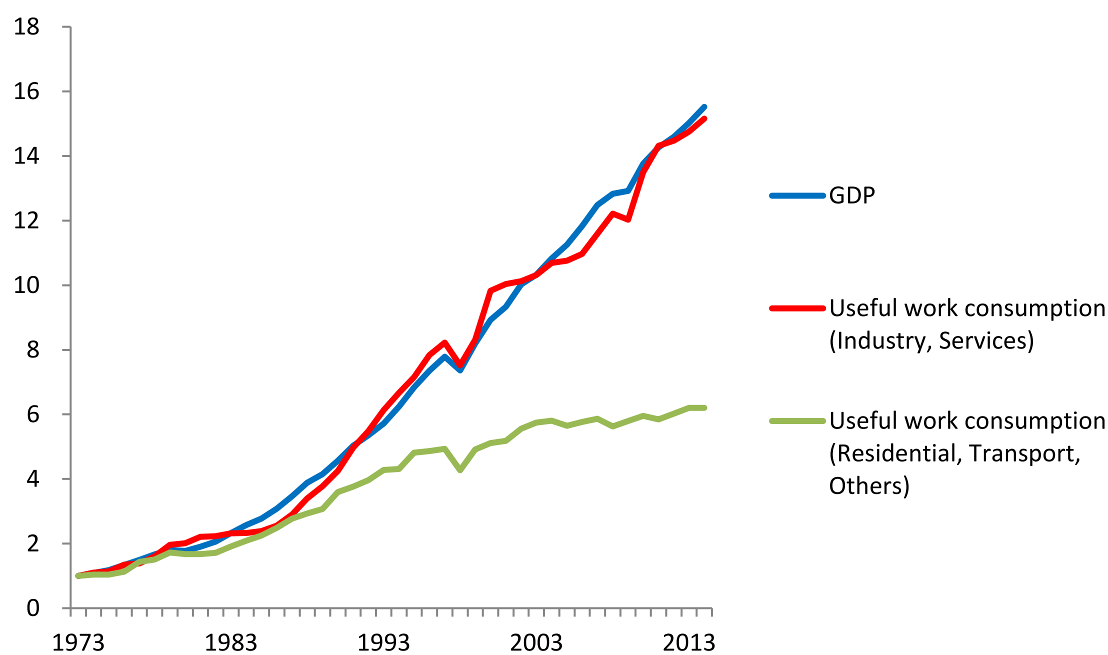


Figure 31: Standardized GDP and Useful Work Consumption of Korea (1973=1)

4.4. Relations between Useful Work and Economic Development of Korea

Korea's useful work consumption has shown very similar behavior with real GDP. Energy (useful work) has been an important factor for Korea's economic development, and securing stable supply of energy sources required for industrial production has been a main concern of policy makers. Korea's useful work consumption has been affected by economic growth, changes of industrial structures, and energy policies of the government. In particular, economic shocks, such as oil shocks in the 1970s, and the financial crisis in the late 1990s, had large impacts not only on the Korean economy but also on useful work consumption (Figure 32). The relationship between useful work and economic growth in Korea is more deeply understood when looking at Korea's economic development history and the evolution of useful work consumption.

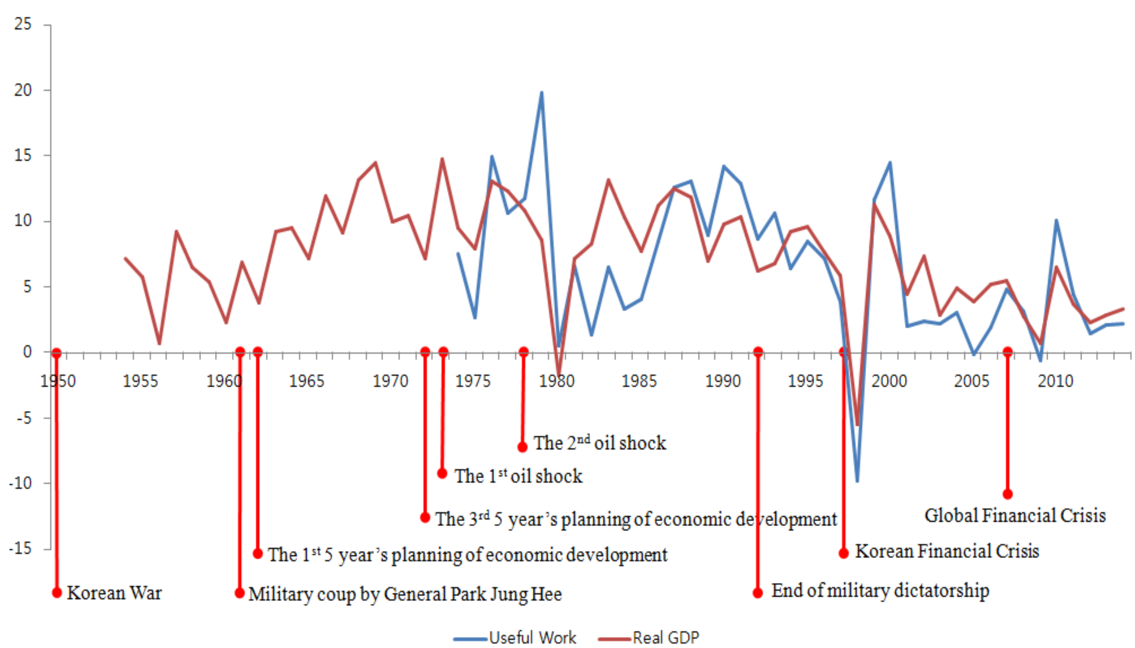


Figure 32: Growth Rate of Useful Work and GDP of Korea (%/year)

After the Korean War in the early 1950s, the Korean economy stagnated due to the lack of capital, poor infrastructure, underdeveloped technology, and narrow domestic market. Policymakers set upon stimulating economic growth by an import-substitution industrialization (ISI) strategy and promoted indigenous industrial firms by giving them privileges to buy foreign currencies and borrow money from bank at preferential rates. The Korean government erected tariff barriers and imposed a prohibition on manufacturing imports to give domestic companies a chance to improve competitiveness through learning by doing and by importing advanced technology. However, these attempts made little difference, and the result was the collapse of the First Republic in April 1960 (EH.net, undated).

During this period, Korea experienced a lack of energy supply, and the major source of energy was firewood, which accounted for more than 50% of Korea's total energy consumption until the early 1960s. The Korean government has tried to promote the production of domestic energy resources such as anthracites and hydro power to cope with the lack of an energy supply. Korea Coal Corporation was established in 1950 to promote domestic coal production. Korea Electric Power Company was established in 1961 by merging three electric companies, and new hydroelectric power plants were built to overcome power shortages (NAK, 2014).

The military coup led by General Park Chung Hee overthrew the short-lived Second Republic in May 1961, and after that point the industrialization of Korea accelerated. The '1st 5 year's planning of economic development' was implemented in 1962 which promoted light industry such as textiles, garments, wig, footwear, and simple electronics. There has also been a shift in economic policy from import-substitution industrialization (ISI) to export promotion (EP) strategy. Under the export promotion strategy, the Korean government gave various types of favors, including low interest loans and tax exemption, to exporting firms according to their export performance. As a result, Korea's export of industrial products has increased rapidly, which became a major source of foreign exchange and capital (Eh.net, undated).

Between 1962 and 1973, Korea’s real GDP has increased by 10% annually which drove rapid growth of energy consumption. Korea’s energy policy in the 1960s mainly focused on the stabilization of an energy supply required for economic development. In this period, Korea Oil Corporation (1962) and Korea Resources Corporation (1967) were established, and many power plants were constructed. However, useful work consumption has increased more slowly than GDP because the Korean economy was still highly dependent on labor-intensive light industries. In this period, petroleum dependence increased from 9.8% in 1962 to 53.8% in 1973, becoming a major energy source for industry. Firewood was replaced by anthracite produced in domestic coal mines and the proportion of firewood in total energy consumption decreased from 51.7% to 14.7% during the same period (NAK, 2014)

In 1972, the Korean government established the ‘3rd 5 year’s planning of economic development’ which aimed to foster heavy and chemical industries such as iron and steel, shipbuilding, petrochemicals, and machinery. The government established industrial parks throughout the country and intervened heavily in the market to allocate limited resources more efficiently. It provided many favors including low interest loans and tax exemptions to Chaebols - conglomerates of businesses owned by a single family - which determined the basic structure of Korean economy thereafter. In the 1970s, the Korean economy has shifted from primary industry to secondary industry, and the foundation for the heavy and chemical industry was laid, which made Korea an energy intensive economy (EH.net, undated). From 1973 to 1979, Korea’s GDP and useful work consumption both increased by 11% annually (Appendix: Table B.1). The dependence on oil has also increased due to the growing demand in industries (Figure 33).

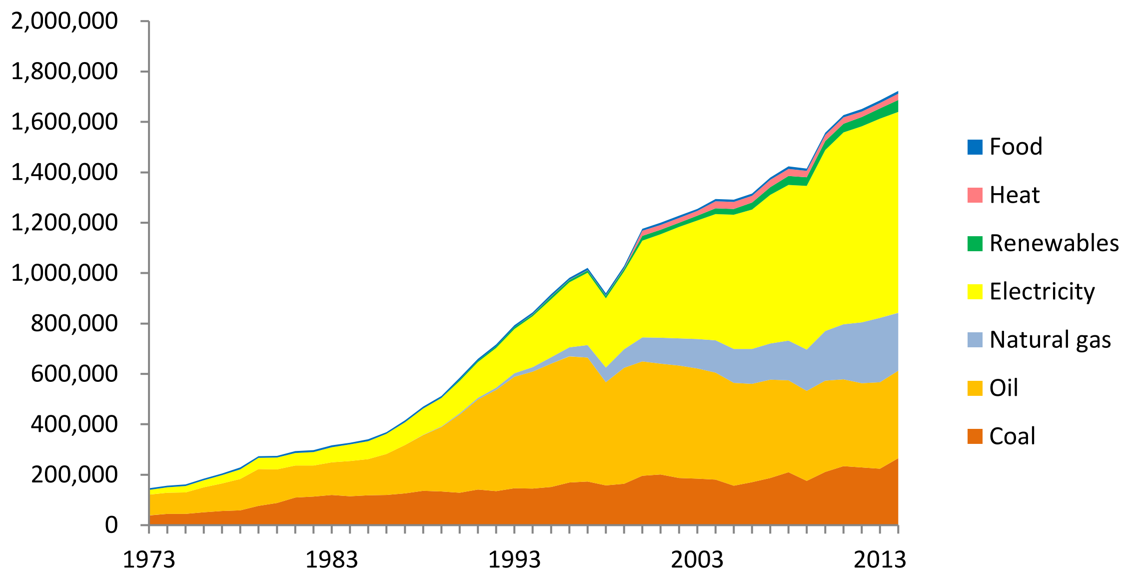


Figure 33: Korea's Useful Work Consumption by Source (TJ)

The 2nd oil shock in 1978 had a large impact on Korean economy. Korea recorded negative growth of export in 1979 for the first time since 1960, and real GDP also decreased by 1.7% in 1980. After the assassination of president Park Chung Hee in 1979, Korea was again brought under the control of the military. The new government focused on stabilizing the economy and adjusting economic imbalances such as over investment, inflation, and excessive debt caused by rapid economic growth and unbalanced economic policies. The government discontinued policies to select and nurture specific industries and tried to promote small and medium-size companies. It also tried to curb inflation and suppressed the wage increase of workers (KDI, 2013).

In the energy industry, policymakers became alerted to the excessive dependence on oil and actively implemented post-oil policies. They also began to worry about environmental problems. Oil was replaced by low-priced coals in industry and power generation. The importance of nuclear power has grown gradually since the first operation of Gori-1 nuclear power plant in 1978 (Korea Hydro and Nuclear Power Corporation, 2013,). To substitute residential coal and oil consumption, the Korea Gas Corporation (KOGAS) was established in 1983 and LNG began to be used at home (KNA, 2014). In 1980, the government established the Korean Energy Agency (KEA) to deal with energy demand and to conserve energy (KEA, undated). Between 1980 and 1989, Korea's real GDP and useful work consumption increased by 8.7% and 7.1% annually and the shares of LNG and nuclear began to increase (Figure 34; Appendix: Table B.1).

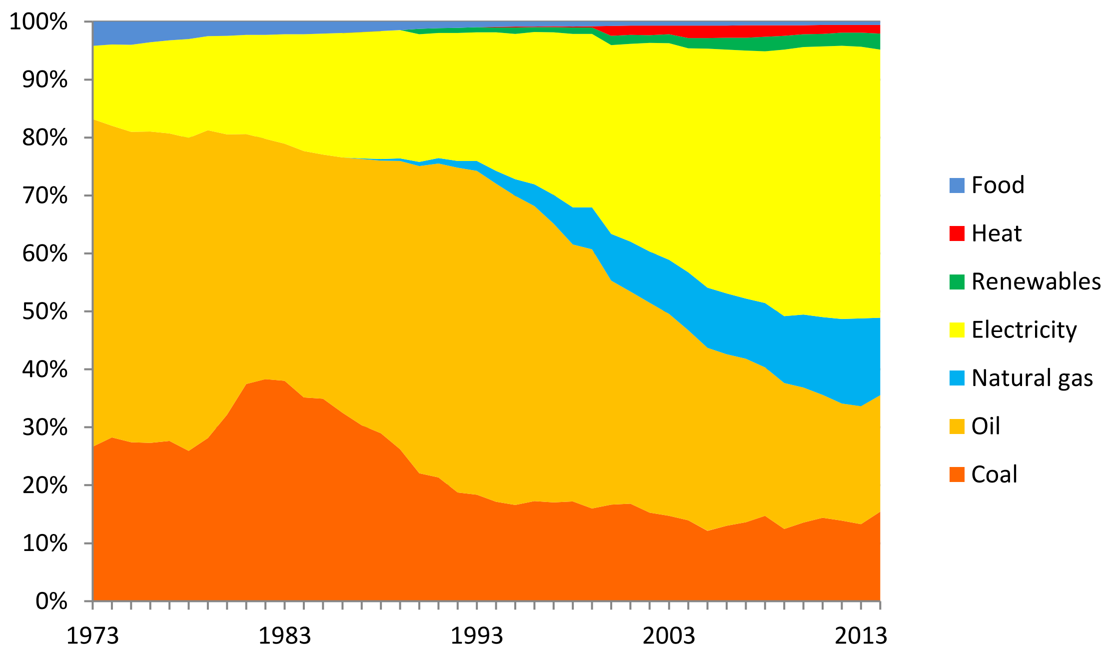


Figure 34: Percentage of Energy Carriers in Total Useful Work Consumption

Post oil policies after the oil shocks contributed somewhat to preventing the rapid growth of oil consumption, but their effects ended in the mid-1980s, and a transition from coal to oil accelerated. Since the late 1980s, the Korean government has begun to reduce subsidies for domestic coal mines which promoted the withdrawal of less economically viable coal mines. Oil consumption has accelerated due to the growing industrial demand and increasing number of cars. The increase of per capita income and strengthened environmental regulations contributed to the reduction of coal consumption at home and raised natural gas and electricity consumption significantly (Figure 33).

In 1992, the military dictatorship, continued since the 1961 military coup, ended and Kim Young Sam was elected as Korea's first civilian president. In the 1990s, the Korean economy entered into a "golden era". Korea's exports rose rapidly and households increased consumption. There was an investment boom in manufacturing and unemployment rates fell. Based on confidence in the economy, the Korean government actively promoted globalization and liberalization. Korea joined the World Trade Organization (WTO) in 1995 and the Organization for Economic Co-operation and Development (OECD) in 1996. Liberalization of capital and financial markets was implemented step by step, and the rice market was opened to imports in 1993.

Following the major economic streams, there has also been a shift in the energy market from a government-led to a market-oriented direction. Prices of petroleum products and trade of crude oil were liberalized, and the Korea Oil Corporation - a government-owned refining company - was privatized in the 1980s (SK networks, undated). In 2001, the Korea Electric Power Corporation (KEPCO) was divided into six subsidiary power generation companies, and the Korea Power Exchange (KPX) was established to coordinate the wholesale electric power market (Korea Resource Economics Association, 2013). Between 1990 and 1997, Korea's economy and useful work consumption have grown by 8.2% and 8.3%, respectively (Appendix: Table B.1).

The financial crisis in 1997, caused by excessive short-term external debts, highly leveraged corporate and banking sectors, and rapid movement of speculative capital, had a tremendous effect on the Korean economy and energy market (Choi, 2006). In 1998, Korea's real GDP and useful work consumption decreased by 5.5% and 9.8%. Even though Korean economy recovered rapidly with the strong economic reform, Korea lost its fast growth engine, and the increase in useful work consumption slowed down considerably (MOTIE, 2014a). Between 1999 and 2014, Korea's real GDP and useful work consumption has increased by 4.1% and 3.5% annually, which were much lower than their annual growth rates between 1980 and 1996, 8.6% and 8.3% respectively (Appendix: Table B.1).

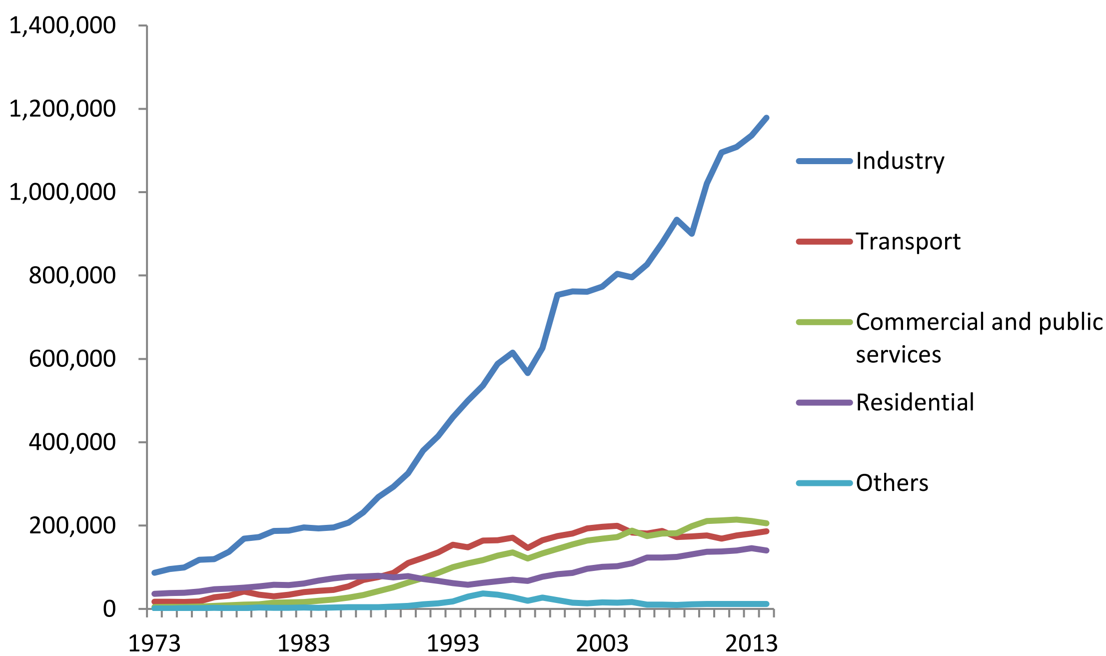


Figure 35: Korea's Useful Work Consumption of Each Sector (TJ)

In the 2000s, high oil prices, economic depression, and increased energy conservation contributed to slowing the increase in useful work consumption. This trend has been observed in most of the economic sectors of Korea. Notably, useful work consumption in the residential and transportation sectors has remained at nearly constant levels in the 2000s, compared to the industry sector (Figure 35). A transition from oil to increased use of natural gas and electricity also progressed in this period. In addition, because of the concerns about environmental problems and climate change issues raised in recent years, the shares of electricity, LNG, and renewable energy in Korea's useful work consumption have increased significantly. As a consequence, Korea's dependence on oil has been decreasing (Figure 34).

5. CONCLUSION

The relationship between energy and the economy of a nation is more clearly verified when looking at useful work rather than at energy consumption because useful work measures the actual services that energy sources provide at the end-use stage of economic activities. Korea's real GDP has increased faster than its energy consumption, but GDP has increased almost similarly to useful work consumption because of improved exegy efficiency. Moreover, their growth rates have shown similar behaviors over the last few decades. Their relationship can also be seen from the economic development history of Korea and changes by useful work intensities.

Korea's useful work consumption has been an important factor for Korea's economic development, and it has been affected by changes of Korea's industrial structure, economic shocks, and energy policies of the government. Korea's industrialization in the 1960s and the 1970s has propelled a rapid increase in useful work consumption until the oil shocks of the 1970s. The first and second oil shocks have contributed to the diversification of energy sources by forcing the government to promote natural gas and nuclear power, which in turn, have made it possible to shape the current diverse energy portfolio of Korea. Increased oil prices forced people and industries to conserve energy, which slightly delayed the growth of useful work consumption in the early 1980s.

In the late 1980s and 1990s, Korea's useful work consumption accelerated again, and petroleum dependence has increased sharply due to increasing demand in the industry and transportation sectors. As peoples' incomes grew, useful work consumption in residential and services sectors also increased. After the financial crisis in 1997, Korea's economic growth has slowed, and the Korean economy entered into a low growth era. As a result, the increase of useful work consumption has also slowed, and its composition has changed. The importance of electricity has grown significantly with Korea's economic development. Growing concerns about the environment and climate change in recent years resulted in the rapid increase in the use natural gas and renewable energy, whereas Korea's dependence on coal and oil has declined.

Korea's economic development has been mainly driven by the industrial sector, and useful work consumption in this sector has increased almost in line with Korea's real GDP. The industrial sector has accounted for more than 60% of Korea's total useful work consumption and has driven the improvement of exergy efficiency. Korea's rapid industrialization and development of heavy and chemical industry have increased the shares of high temperature heat and electric-mechanical drive uses, which have higher exergy efficiencies than do other categories. As a result, the aggregate exergy efficiency of Korea has increased faster than that of other countries. The Korean economy became able to produce more goods and services with less energy inputs, resulting in a slower increase of energy and exergy consumption than in GDP.

As a consequence, energy and exergy intensity have declined during Korea's economic development. However, useful work intensity has declined slightly, but it has been more stable than energy and exergy intensity. On average, Korea consumed 1.4 TJ of useful work to produce 1 billion won of GDP between 1973 and 2014. This shows that there is a more stable relationship between useful work and the economic growth of Korea, rather than energy and exergy consumption. It is clearer when only industry and services sectors are considered because they have shown closer relationship with GDP than other sectors. Actually, Korea's GDP has increased more rapidly than total useful work consumption, and overall useful work intensity has declined slightly. However, if only industry and services sectors are considered, the decreasing trend disappears and useful work intensity becomes more stable.

Appendix A. Data

Product (original unit)	Conversion factor		Product (original unit)	Conversion factor	
Hard coal (kt)	30.00	TJ/kt	Gasoline type jet fuel (kt)	48.17	TJ/kt
Anthracite (kt)	30.00	TJ/kt	Kerosene type jet fuel (kt)	48.06	TJ/kt
Coking coal (kt)	29.30	TJ/kt	Other kerosene (kt)	46.33	TJ/kt
Other bituminous coal (kt)	25.30	TJ/kt	Gas/diesel oil (kt)	45.66	TJ/kt
Sub-bituminous coal (kt)	20.65	TJ/kt	Fuel oil (kt)	44.40	TJ/kt
Lignite (kt)	17.43	TJ/kt	Naphtha (kt)	47.73	TJ/kt
Patent fuel (kt)	28.13	TJ/kt	White spirit & SBP (kt)	46.44	TJ/kt
Coke oven coke (kt)	27.90	TJ/kt	Lubricants (kt)	46.33	TJ/kt
Gas coke (kt)	28.35	TJ/kt	Bitumen (kt)	41.90	TJ/kt
Coal tar (kt)	36.00	TJ/kt	Paraffin waxes (kt)	43.20	TJ/kt
BKB (kt)	17.43	TJ/kt	Petroleum coke (kt)	33.15	TJ/kt
Coke oven gas (TJ-GCV)	1.00	TJ/TJ	Other oil products (kt)	43.20	TJ/kt
Blast furnace gas (TJ-GCV)	1.00	TJ/TJ	Industrial waste (TJ-NCV)	1.20	TJ/TJ
Other recovered gases (TJ-GCV)	1.00	TJ/TJ	Municipal waste (renewable) (TJ-NCV)	1.20	TJ/TJ
Natural gas (TJ-GCV)	1.00	TJ/TJ	Municipal waste (non-renewable) (TJ-NCV)	1.20	TJ/TJ
Natural gas liquids (kt)	45.19	TJ/kt	Primary solid biofuels (TJ-NCV)	1.20	TJ/TJ
Refinery feedstocks (kt)	43.94	TJ/kt	Biogases (TJ-NCV)	1.20	TJ/TJ
Additives/blending components (kt)	42.50	TJ/kt	Biodiesels (kt)	43.33	TJ/kt
Other hydrocarbons (kt)	42.50	TJ/kt	Other liquid biofuels (kt)	34.50	TJ/kt
Refinery gas (kt)	50.51	TJ/kt	Non-specified primary biofuels/waste(TJ-NCV)	1.20	TJ/TJ
Ethane (kt)	51.90	TJ/kt	Geothermal (TJ-GCV)	1.00	TJ/TJ
Liquefied petroleum gases (LPG)(kt)	50.80	TJ/kt	Solar thermal (TJ-GCV)	1.00	TJ/TJ
Motor gasoline (kt)	47.10	TJ/kt	Electricity (GWh)	3.60	TJ/GWh
Aviation gasoline (kt)	47.40	TJ/kt	Heat (TJ-GCV)	1.00	TJ/TJ

Table A.1: Energy Conversion Factors (IEA, 2005, 2008; UN, 1987)

Product	Hard coal	Anth-racite	Coking coal	Other bituminous coal	Sub-bituminous coal	Lignite	Patent fuel	Coke oven coke	Gas coke	Coal tar	BKB	Coke oven gas	Blast furnace gas	Other recovered gases	Natural gas	Natural gas liquids	Refinery feedstocks	Additives/blending components	Other hydro-carbons	Refinery gas	Ethane	Liquefied petroleum gases (LPG)	Motor gasoline excl. biofuels	Aviation gasoline	Gasoline type jet fuel	Kerosene type jet fuel excl. biofuels
Coal mines	M	M	M	M	M	M	M	H	H	M	M	H	H	H	M	M	L(120)	L(120)	L(120)	M	M	GV	GV	M	M	M
Oil and gas extraction	M	M	M	M	M	M	M	H	H	M	M	H	H	H	OM	OM	L(120)	L(120)	L(120)	M	M	OM	OM	M	M	M
Blast furnaces	M	M	M	M	M	M	M	H	H	M	M	H	H	H	M	M	L(120)	L(120)	L(120)	M	M	GV	GV	M	M	M
Gas works	M	M	M	M	M	M	M	H	H	M	M	H	H	H	M	M	L(120)	L(120)	L(120)	M	M	GV	GV	M	M	M
Gasification plants for biogases	M	M	M	M	M	M	M	H	H	M	M	H	H	H	M	M	L(120)	L(120)	L(120)	M	M	GV	GV	M	M	M
Coke ovens	M	M	M	M	M	M	M	H	H	M	M	H	H	H	M	M	L(120)	L(120)	L(120)	M	M	GV	GV	M	M	M
Patent fuel plants	M	M	M	M	M	M	M	H	H	M	M	H	H	H	M	M	L(120)	L(120)	L(120)	M	M	GV	GV	M	M	M
BKB/peat briquette plants	M	M	M	M	M	M	M	H	H	M	M	H	H	H	M	M	L(120)	L(120)	L(120)	M	M	GV	GV	M	M	M
Oil refineries	M	M	M	M	M	M	M	H	H	M	M	H	H	H	M	M	L(120)	L(120)	L(120)	M	M	GV	GV	M	M	M
Coal liquefaction plants	M	M	M	M	M	M	M	H	H	M	M	H	H	H	M	M	L(120)	L(120)	L(120)	M	M	GV	GV	M	M	M
Liquefaction (LNG) / regasification plants	M	M	M	M	M	M	M	H	H	M	M	H	H	H	OM	OM	L(120)	L(120)	L(120)	M	M	OM	OM	M	M	M
Gas-to-liquids (GTL) plants	M	M	M	M	M	M	M	H	H	M	M	H	H	H	OM	OM	L(120)	L(120)	L(120)	M	M	OM	OM	M	M	M
Own use in electricity, CHP and heat plants	M	M	M	M	M	M	M	H	H	M	M	H	H	H	OM	OM	L(120)	L(120)	L(120)	M	M	OM	OM	M	M	M
Pumped storage plants	M	M	M	M	M	M	M	H	H	M	M	H	H	H	OM	OM	L(120)	L(120)	L(120)	M	M	OM	OM	OM	OM	OM
Nuclear industry	M	M	M	M	M	M	M	H	H	M	M	H	H	H	M	M	L(120)	L(120)	L(120)	M	M	GV	GV	M	M	M
Charcoal production plants	M	M	M	M	M	M	M	H	H	M	M	H	H	H	M	M	L(120)	L(120)	L(120)	M	M	GV	GV	M	M	M
Non-specified	M	M	M	M	M	M	M	H	H	M	M	H	H	H	M	M	L(120)	L(120)	L(120)	M	M	GV	GV	M	M	M
Iron and steel	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H
Chemical and petrochemical	M	M	M	M	M	M	M	H	H	H	H	H	H	H	H	M	M	M	M	M	M	M	GV	A	A	A
Non-ferrous metals	M	M	M	M	M	M	M	H	H	H	H	H	H	H	H	M	M	M	M	M	M	M	GV	A	A	A
Non-metallic minerals	M	M	H	H	H	H	M	H	H	H	H	H	H	H	H	M	M	M	M	M	M	M	GV	A	A	A
Transport equipment	M	M	M	M	M	M	M	H	H	H	H	H	H	H	H	M	M	M	M	M	M	M	GV	A	A	A
Machinery	M	M	M	M	M	M	M	H	H	H	H	H	H	H	H	M	M	M	M	M	M	M	GV	A	A	A
Mining and quarrying	M	M	M	M	M	M	M	H	H	H	H	H	H	H	H	M	M	M	M	M	M	M	GV	A	A	A
Food and tobacco	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	GV	A	A	A
Paper, pulp and print	L(120)	L(120)	L(120)	L(120)	L(120)	L(120)	L(120)	M	M	M	M	M	M	M	M	M	L(120)	L(120)	L(120)	L(120)	L(120)	L(120)	GV	A	A	A
Wood and wood products	L(120)	L(120)	L(120)	L(120)	L(120)	L(120)	L(120)	M	M	M	M	M	M	M	M	M	L(120)	L(120)	L(120)	L(120)	L(120)	L(120)	GV	A	A	A
Construction	L(120)	L(120)	L(120)	L(120)	L(120)	L(120)	L(120)	M	M	M	M	M	M	M	M	M	L(120)	L(120)	L(120)	L(120)	L(120)	L(120)	GV	A	A	A
Textile and leather	L(120)	L(120)	L(120)	L(120)	L(120)	L(120)	L(120)	M	M	M	M	M	M	M	M	M	L(120)	L(120)	L(120)	L(120)	L(120)	L(120)	GV	A	A	A
Non-specified (industry)	M	M	M	M	M	M	M	H	H	H	H	H	H	H	H	M	M	M	M	M	M	M	GV	A	A	A
Domestic aviation	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Road	-	-	-	-	-	-	-	-	-	-	-	-	-	-	NV	-	-	-	-	-	-	GV	GV	-	-	-
Rail	SL	SL	SL	SL	SL	SL	SL	SL	SL	SL	SL	SL	SL	SL	DV	SL	SL	SL	SL	SL	GV	GV	GV	GV	GV	GV
Pipeline transport	CM	CM	CM	CM	CM	CM	CM	CM	CM	CM	CM	CM	CM	CM	OM	OM	OM	OM	OM	OM	OM	OM	OM	OM	OM	OM
Domestic navigation	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Non-specified (transport)	SL	SL	SL	SL	SL	SL	SL	SL	SL	SL	SL	SL	SL	SL	NV	DV	DV	DV	DV	DV	DV	DV	GV	DV	DV	DV
Residential	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	OM	OM	OM	OM	OM
Commercial and public services	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	OM	OM	OM	OM	OM
Agriculture/forestry	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	OM	OM	OM	OM	OM
Fishing	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	OM	OM	OM	OM	OM
Non-specified (other)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	OM	OM	OM	OM	OM

Product	Other kerosene	Gas/diesel oil excl. biofuels	Fuel oil	Naphtha	White spirit & SBP	Lubricants	Bitumen	Paraffin waxes	Petroleum coke	Other oil products	Industrial waste	Municipal waste (renewable)	Municipal waste (non-renewable)	Primary solid biofuels	Biogases	Biodiesels	Other liquid biofuels	Non-specified primary biofuels/waste	Geothermal	Solar thermal	Other sources	Electricity	Heat
Coal mines	M	OM	M	-	M	-	M	L(120)	M	M	M	L(120)	L(120)	L(120)	M	DV	GV	L(120)	-	CHP-L(50)	L(120)	EI	CHP-M
Oil and gas extraction	M	OM	M	-	M	-	M	L(120)	M	M	M	L(120)	L(120)	L(120)	M	DV	GV	L(120)	-	CHP-L(50)	L(120)	EI	CHP-M
Blast furnaces	M	OM	M	-	M	-	M	L(120)	M	M	M	L(120)	L(120)	L(120)	M	DV	GV	L(120)	-	CHP-L(50)	L(120)	EI	CHP-M
Gas works	M	OM	M	-	M	-	M	L(120)	M	M	M	L(120)	L(120)	L(120)	M	DV	GV	L(120)	-	CHP-L(50)	L(120)	EI	CHP-M
Gasification plants for biogases	M	OM	M	-	M	-	M	L(120)	M	M	M	L(120)	L(120)	L(120)	M	DV	GV	L(120)	-	CHP-L(50)	L(120)	EI	CHP-M
Coke ovens	M	OM	M	-	M	-	M	L(120)	M	M	M	L(120)	L(120)	L(120)	M	DV	GV	L(120)	-	CHP-L(50)	L(120)	EI	CHP-M
Patent fuel plants	M	OM	M	-	M	-	M	L(120)	M	M	M	L(120)	L(120)	L(120)	M	DV	GV	L(120)	-	CHP-L(50)	L(120)	EI	CHP-M
BKB/peat briquette plants	M	OM	M	-	M	-	M	L(120)	M	M	M	L(120)	L(120)	L(120)	M	DV	GV	L(120)	-	CHP-L(50)	L(120)	EI	CHP-M
Oil refineries	M	OM	M	-	M	-	M	L(120)	M	M	M	L(120)	L(120)	L(120)	M	DV	GV	L(120)	-	CHP-L(50)	L(120)	EI	CHP-M
Coal liquefaction plants	M	OM	M	-	M	-	M	L(120)	M	M	M	L(120)	L(120)	L(120)	M	DV	GV	L(120)	-	CHP-L(50)	L(120)	EI	CHP-M
Liquefaction (LNG) / regasification plants	M	OM	M	-	M	-	M	L(120)	M	M	M	L(120)	L(120)	L(120)	M	OM	OM	L(120)	-	CHP-L(50)	L(120)	EI	CHP-M
Gas-to-liquids (GTL) plants	M	OM	M	-	M	-	M	L(120)	M	M	M	L(120)	L(120)	L(120)	M	OM	OM	L(120)	-	CHP-L(50)	L(120)	EI	CHP-M
Own use in electricity, CHP and heat plants	M	OM	OM	-	M	-	M	L(120)	M	M	M	L(120)	L(120)	L(120)	M	DV	GV	L(120)	-	CHP-L(50)	L(120)	EI	CHP-M
Pumped storage plants	OM	OM	OM	-	M	-	M	L(120)	M	M	M	L(120)	L(120)	L(120)	M	OM	OM	L(120)	-	CHP-L(50)	L(120)	EI	CHP-M
Nuclear industry	M	OM	M	-	M	-	M	L(120)	M	M	M	L(120)	L(120)	L(120)	M	DV	GV	L(120)	-	CHP-L(50)	L(120)	EI	CHP-M
Charcoal production plants	M	DV	M	-	M	-	M	L(120)	M	M	M	L(120)	L(120)	L(120)	M	OM	GV	L(120)	-	CHP-L(50)	L(120)	EI	CHP-M
Non-specified	M	OM	M	-	M	-	M	L(120)	M	M	M	L(120)	L(120)	L(120)	M	DV	GV	L(120)	-	CHP-L(50)	L(120)	EI	CHP-M
Iron and steel	H	H	H	H	H	H	H	H	H	H	H	H	H	M	H	H	H	H	CHP-M	CHP-L(120)	M	EI	CHP-M
Chemical and petrochemical	M	OM	M	M	M	M	M	M	M	M	M	M	M	L(120)	H	H	H	L(120)	CHP-M	CHP-L(120)	M	EI	CHP-M
Non-ferrous metals	M	OM	M	M	M	M	M	M	M	M	M	M	M	L(120)	H	H	H	L(120)	CHP-M	CHP-L(120)	M	EI	CHP-M
Non-metallic minerals	M	OM	M	M	M	M	M	M	M	M	H	M	M	L(120)	H	H	H	L(120)	CHP-M	CHP-L(120)	M	EI	CHP-M
Transport equipment	M	OM	M	M	M	M	M	M	M	M	M	M	M	L(120)	H	H	H	L(120)	CHP-M	CHP-L(120)	M	EI	CHP-M
Machinery	M	OM	M	M	M	M	M	M	M	M	M	M	M	L(120)	H	H	H	L(120)	CHP-M	CHP-L(120)	M	EI	CHP-M
Mining and quarrying	M	OM	M	M	M	M	M	M	M	M	M	M	M	L(120)	H	H	H	L(120)	CHP-M	CHP-L(120)	M	EI	CHP-M
Food and tobacco	A	DV	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	CHP-L(50)	CHP-L(50)	M	EI	CHP-L(50)
Paper, pulp and print	A	DV	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(120)	L(120)	L(120)	L(120)	L(120)	L(120)	L(120)	L(120)	L(120)	CHP-L(120)	CHP-L(90)	M	EI	CHP-L(120)
Wood and wood products	A	DV	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(120)	L(120)	L(120)	L(120)	L(120)	L(120)	L(120)	L(120)	L(120)	CHP-L(120)	CHP-L(90)	M	EI	CHP-L(120)
Construction	A	DV	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(120)	L(120)	L(120)	L(120)	L(120)	L(120)	L(120)	L(120)	L(120)	CHP-L(120)	CHP-L(90)	M	EI	CHP-L(120)
Textile and leather	A	OM	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(120)	L(120)	L(120)	L(120)	L(120)	L(120)	L(120)	L(120)	L(120)	CHP-L(120)	CHP-L(90)	M	EI	CHP-L(120)
Non-specified (industry)	M	OM	M	M	M	M	M	M	M	M	M	M	M	L(120)	H	H	H	L(120)	CHP-M	CHP-L(120)	M	EI	CHP-M
Domestic aviation	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	EO	A
Road	DV	DV	DV	-	-	-	-	-	-	-	-	-	-	-	GV	DV	DV	DV	-	-	-	EO	-
Rail	GV	DV	DV	SL	SL	SL	SL	SL	SL	SL	SL	SL	SL	SL	DV	DV	DV	DV	-	-	SL	EO	SL
Pipeline transport	OM	OM	OM	OM	OM	OM	OM	OM	OM	OM	L(120)	L(120)	L(120)	L(120)	OM	OM	OM	OM	-	CHP-L(50)	-	EO	-
Domestic navigation	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	EO	N
Non-specified (transport)	DV	DV	DV	DV	DV	DV	DV	DV	DV	DV	SL	SL	SL	SL	NV	DV	GV	SL	-	-		EO	-
Residential	CL	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	CHP-L(50)	EO	L(50)
Commercial and public services	CL	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	CHP-L(50)	EO	L(50)
Agriculture/forestry	CL	DV	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(50)	L(50)	CHP-L(50)	EO	L(50)
Fishing	CL	DV	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(90)	L(50)	L(50)	CHP-L(50)	EO	L(50)
Non-specified (other)	CL	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	L(50)	CHP-L(50)	EO	L(50)

Table A.2: Criteria for Allocating Exergy Values to Useful Work Categories (Serrenho et al., 2014)

End-uses		1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983
Industries	Heat	49.7%	49.0%	48.4%	47.7%	47.1%	46.4%	45.8%	45.2%	44.7%	44.3%	43.8%
	Mechanical drive	8.2%	8.3%	8.5%	8.7%	8.9%	9.0%	9.2%	9.4%	9.5%	9.7%	9.9%
	Light	14.8%	15.4%	16.1%	16.8%	17.5%	18.1%	18.8%	19.5%	20.2%	20.8%	21.5%
	Other electric uses	27.4%	27.2%	27.0%	26.8%	26.6%	26.4%	26.2%	26.0%	25.6%	25.2%	24.8%
Others	Heat	13.7%	14.0%	14.4%	14.8%	15.1%	15.4%	15.7%	16.0%	16.3%	16.6%	16.9%
	Mechanical drive	26.9%	27.3%	27.7%	28.0%	28.4%	28.7%	29.0%	29.2%	29.5%	30.0%	30.4%
	Light	32.1%	31.5%	30.9%	30.5%	29.9%	29.5%	29.1%	28.8%	28.5%	28.2%	27.9%
	Other electric uses	27.4%	27.2%	27.0%	26.8%	26.6%	26.4%	26.2%	26.0%	25.6%	25.2%	24.8%
End-uses		**1984**	**1985**	**1986**	**1987**	**1988**	**1989**	**1990**	**1991**	**1992**	**1993**	**1994**
Industries	Heat	43.4%	43.0%	42.5%	42.1%	41.6%	41.2%	40.7%	40.6%	41.2%	41.9%	42.5%
	Mechanical drive	10.0%	10.2%	10.4%	10.5%	10.7%	10.9%	11.0%	11.2%	11.2%	11.2%	11.2%
	Light	22.2%	22.9%	23.5%	24.2%	24.9%	25.6%	26.2%	26.9%	26.9%	26.9%	26.9%
	Other electric uses	24.4%	24.0%	23.6%	23.2%	22.8%	22.4%	22.0%	21.3%	20.7%	20.0%	19.4%
Others	Heat	17.3%	17.6%	18.0%	18.3%	18.0%	18.1%	18.7%	19.2%	19.5%	19.7%	19.9%
	Mechanical drive	30.9%	31.2%	31.5%	31.7%	31.8%	32.7%	31.7%	32.5%	32.8%	33.6%	33.9%
	Light	27.5%	27.1%	27.0%	26.8%	27.4%	26.9%	27.6%	27.0%	27.0%	26.8%	26.8%
	Other electric uses	24.4%	24.0%	23.6%	23.2%	22.8%	22.4%	22.0%	21.3%	20.7%	20.0%	19.4%
End-uses		**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**
	Heat	43.2%	43.9%	44.5%	45.2%	45.8%	46.5%	47.2%	47.8%	48.5%	49.1%	49.8%
	Mechanical drive	11.2%	11.2%	11.2%	11.2%	11.2%	11.2%	11.2%	11.2%	11.2%	11.2%	11.2%
	Light	26.9%	26.9%	26.9%	26.9%	26.9%	26.9%	26.9%	26.9%	26.9%	26.9%	26.9%
	Other electric uses	18.7%	18.0%	17.4%	16.7%	16.1%	15.4%	14.7%	14.1%	13.4%	12.8%	12.1%
Others	Heat	20.3%	20.6%	20.8%	20.8%	20.9%	21.0%	21.2%	21.4%	21.6%	21.7%	21.9%
	Mechanical drive	33.8%	33.8%	33.8%	34.1%	34.5%	34.9%	34.8%	34.8%	34.9%	34.8%	34.9%
	Light	27.2%	27.6%	28.1%	28.3%	28.5%	28.7%	29.3%	29.8%	30.2%	30.6%	31.1%
	Other electric uses	18.7%	18.0%	17.4%	16.7%	16.1%	15.4%	14.7%	14.1%	13.4%	12.8%	12.1%
End-uses		**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**		
Industries	Heat	50.5%	51.1%	51.8%	52.4%	52.4%	52.4%	52.4%	52.4%	52.4%		
	Mechanical drive	11.2%	11.2%	11.2%	11.2%	11.2%	11.2%	11.2%	11.2%	11.2%		
	Light	26.9%	26.9%	26.9%	26.9%	26.9%	26.9%	26.9%	26.9%	26.9%		
	Other electric uses	11.4%	10.8%	10.1%	9.5%	9.5%	9.5%	9.5%	9.5%	9.5%		
Others	Heat	21.8%	21.6%	21.4%	24.4%	24.4%	24.4%	24.4%	24.4%	24.4%		
	Mechanical drive	34.8%	34.8%	34.9%	33.3%	33.3%	33.3%	33.3%	33.3%	33.3%		
	Light	32.0%	32.8%	33.6%	32.9%	32.9%	32.9%	32.9%	32.9%	32.9%		
	Other electric uses	11.4%	10.8%	10.1%	9.5%	9.5%	9.5%	9.5%	9.5%	9.5%		

* The shares of each electricity end-use are assumed to be constant after 2009

Table A.3: Shares of Electricity End-Uses (Serrenho et al., 2014)

Useful work category	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986
Fuel – High Temp. Heat (500°C)	0.39	0.39	0.39	0.40	0.40	0.40	0.40	0.40	0.41	0.41	0.41	0.41	0.42	0.42
Fuel – Medium Temp. Heat (150°C)	0.20	0.20	0.20	0.20	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.22
Fuel – Low Temp. Heat (120°C)	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Fuel – Low Temp. Heat (90°C)	0.13	0.13	0.13	0.13	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14
Fuel – Low Temp. Heat (50°C)	0.07	0.07	0.07	0.07	0.07	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
CHP/Heat – Medium Temp. Heat (150°C)	0.53	0.54	0.54	0.54	0.55	0.55	0.55	0.55	0.56	0.56	0.56	0.57	0.57	0.57
CHP/Heat – Low Temp. Heat (120°C)	0.45	0.45	0.45	0.46	0.46	0.46	0.46	0.47	0.47	0.47	0.47	0.48	0.48	0.48
CHP/Heat – Low Temp. Heat (90°C)	0.35	0.35	0.35	0.36	0.36	0.36	0.36	0.36	0.37	0.37	0.37	0.37	0.37	0.38
CHP/Heat – Low Temp. Heat (50°C)	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.19	0.19
Steam locomotives	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
Coal – Stationary Mech. Drive	0.34	0.34	0.34	0.34	0.34	0.35	0.35	0.35	0.35	0.35	0.36	0.36	0.36	0.36
Diesel vehicles	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Gasoline/LPG vehicles	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Aviation	0.18	0.18	0.18	0.19	0.19	0.19	0.20	0.20	0.20	0.21	0.21	0.21	0.22	0.22
Oil – Stationary Mech. Drive	0.34	0.34	0.34	0.34	0.34	0.35	0.35	0.35	0.35	0.35	0.36	0.36	0.36	0.36
Navigation	0.34	0.34	0.34	0.34	0.34	0.35	0.35	0.35	0.35	0.35	0.36	0.36	0.36	0.36
Diesel-electric	0.26	0.27	0.27	0.27	0.27	0.28	0.28	0.28	0.28	0.28	0.29	0.29	0.29	0.29
Natural gas vehicles	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
Coal/Oil Light	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03

Useful work category	1987	1988	1991	1989	1990	1992	1993	1994	1995	1996	1997	1998	1999	2000
Fuel – High Temp. Heat (500°C)	0.42	0.42	0.43	0.42	0.43	0.43	0.43	0.43	0.44	0.44	0.44	0.44	0.45	0.45
Fuel – Medium Temp. Heat (150°C)	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.23	0.23	0.23	0.23	0.23	0.23
Fuel – Low Temp. Heat (120°C)	0.18	0.18	0.19	0.18	0.18	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19
Fuel – Low Temp. Heat (90°C)	0.14	0.14	0.15	0.14	0.14	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Fuel – Low Temp. Heat (50°C)	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
CHP/Heat – Medium Temp. Heat (150°C)	0.57	0.58	0.59	0.58	0.58	0.59	0.59	0.60	0.60	0.60	0.60	0.61	0.61	0.61
CHP/Heat – Low Temp. Heat (120°C)	0.48	0.49	0.49	0.49	0.49	0.50	0.50	0.50	0.50	0.51	0.51	0.51	0.51	0.52
CHP/Heat – Low Temp. Heat (90°C)	0.38	0.38	0.39	0.38	0.38	0.39	0.39	0.39	0.39	0.40	0.40	0.40	0.40	0.40
CHP/Heat – Low Temp. Heat (50°C)	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.20	0.20
Steam locomotives	0.07	0.07	0.07	0.07	0.07	-	-	-	-	-	-	-	-	-
Coal – Stationary Mech. Drive	0.36	0.36	0.37	0.37	0.37	0.37	0.37	0.37	0.38	0.38	0.38	0.38	0.38	0.38
Diesel vehicles	0.12	0.12	0.13	0.12	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13
Gasoline/LPG vehicles	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Aviation	0.22	0.23	0.24	0.23	0.23	0.24	0.24	0.25	0.25	0.25	0.26	0.26	0.26	0.26
Oil – Stationary Mech. Drive	0.36	0.36	0.37	0.37	0.37	0.37	0.37	0.37	0.38	0.38	0.38	0.38	0.38	0.38
Navigation	0.36	0.36	0.37	0.37	0.37	0.37	0.37	0.37	0.38	0.38	0.38	0.38	0.38	0.38
Diesel-electric	0.30	0.30	0.31	0.30	0.30	0.31	0.31	0.31	0.32	0.32	0.32	0.32	0.32	0.33
Natural gas vehicles	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
Coal/Oil Light	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03

Useful work category	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Fuel – High Temp. Heat (500°C)	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Fuel – Medium Temp. Heat (150°C)	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23
Fuel – Low Temp. Heat (120°C)	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19
Fuel – Low Temp. Heat (90°C)	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Fuel – Low Temp. Heat (50°C)	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
CHP/Heat – Medium Temp. Heat (150°C)	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61
CHP/Heat – Low Temp. Heat (120°C)	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52
CHP/Heat – Low Temp. Heat (90°C)	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
CHP/Heat – Low Temp. Heat (50°C)	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Steam locomotives	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Coal – Stationary Mech. Drive	0.39	0.39	0.39	0.39	0.39	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Diesel vehicles	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13
Gasoline/LPG vehicles	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Aviation	0.27	0.27	0.27	0.28	0.28	0.28	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29
Oil – Stationary Mech. Drive	0.39	0.39	0.39	0.39	0.39	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Navigation	0.39	0.39	0.39	0.39	0.39	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Diesel-electric	0.33	0.33	0.33	0.34	0.34	0.34	0.34	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Natural gas vehicles	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
Coal/Oil Light	0.03	0.03	0.03	0.03	0.03	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04

* Exergy efficiencies are assumed to be constant after 2009.

* Reference environment temperature of heat categories

- Service heat temperatures over 50℃: 12.4℃(Average annual temperature of Seoul, 1973-2014)
- Service heat temperatures with 50℃: -0.81℃(Average winter(Dec-Feb) temperature of Seoul, 1973-2014)

Table A.4: Exergy Efficiency of Each Category (Serrenho et al., 2014; KMA, 2017)

Useful work category	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986
Low temperature heat	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.20	0.20	0.20	0.20
Mechanical drive	0.78	0.79	0.79	0.79	0.79	0.80	0.80	0.80	0.80	0.81	0.81	0.81	0.81	0.82
Light	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Other Electric Uses	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.17	0.17	0.17	0.16	0.16

Useful work category	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Low temperature heat	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.19	0.19	0.19	0.19
Mechanical drive	0.82	0.82	0.82	0.83	0.83	0.83	0.83	0.84	0.84	0.84	0.84	0.85	0.85	0.85
Light	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Other Electric Uses	0.16	0.15	0.15	0.14	0.14	0.14	0.14	0.13	0.13	0.13	0.12	0.12	0.12	0.11

Useful work category	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Low temperature heat	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19
Mechanical drive	0.85	0.86	0.86	0.86	0.86	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87
Light	0.03	0.03	0.03	0.03	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Other Electric Uses	0.11	0.11	0.10	0.10	0.10	0.10	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09

* Reference environment temperatures for low temperature heat category
  - Industry: 12.4℃(Average annual temperature of Seoul, 1973-2014)
  - Others: -0.81℃(Average winter(Dec-Feb) temperature of Seoul, 1973-2014)

* Temperatures of heating services used for low temperature heat category (assumption)
  - Industry: 120℃
  - Others: 50℃

* Energy efficiency(η) of the heat category using electricity as an input was assumed to be 100%

Table A.5: Exergy Efficiency of Electricity End-uses (Serrenho et al., 2014; KMA, 2017)

Appendix B. Results

Useful work category	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986
High temperature heat	9767	13541	13225	17448	20162	21745	38531	47498	81413	86429	88797	78254	77073	76091
Medium temperature heat	48449	49921	50414	56355	57913	69089	74973	72214	34742	31369	32699	33365	31293	34350
Low temperature heat	33149	34997	35978	39371	46100	46608	47799	53396	72783	69558	72763	80982	86060	91017
Mechanical drive	46065	49633	52044	61697	69373	78627	98557	88002	90044	95038	106538	117908	128597	149559
Light	621	629	782	887	1257	1774	2361	2278	2148	2179	2265	2431	2488	2622
Other electric uses	1781	2058	2354	2789	3290	4026	4719	5028	5472	5868	6568	7268	7804	8612
Muscle work	6107	6150	6418	6632	6632	6878	6907	6754	6735	6769	6897	7097	7052	7231
Total useful work(TJ)	145940	156928	161215	185178	204728	228747	273846	275170	293336	297210	316527	327305	340367	369482
Total exergy(TJ)	1100352	1136248	1171214	1293470	1453068	1578744	1751583	1784507	1822620	1807131	1920303	2049522	2139212	2293984
Final energy consumption(TJ)	866281	899619	925270	1035279	1186663	1299244	1462834	1498784	1536364	1521380	1625495	1742535	1829209	1971225
Total exergy efficiency	0.13	0.14	0.14	0.14	0.14	0.14	0.16	0.15	0.16	0.16	0.16	0.16	0.16	0.16
Real GDP(B₩)	91938	100636	108549	122786	137861	152715	165887	163065	174774	189219	214276	236652	254992	283612
Population	34103149	34692266	35280725	35848523	36411795	36969185	37534236	38123775	38723248	39326352	39910403	40405956	40805744	41213674

Useful work category	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
High temperature heat	81443	92480	97503	99402	122885	129045	151687	157424	166605	189268	193940	179369	198461	240053
Medium temperature heat	40984	51684	61346	73337	89501	104555	112540	125275	126479	130967	134775	127983	142724	159796
Low temperature heat	93256	97368	97587	105763	103364	100930	101867	105298	110271	113847	116994	104587	115358	126665
Mechanical drive	180496	206660	231887	279036	315295	350345	391902	417436	468750	498763	522473	461570	518769	592553
Light	2832	3365	4257	6226	6461	8218	10069	11231	14046	16444	17704	13635	17614	17344
Other electric uses	9743	11290	12245	13896	15218	16425	17824	19928	21959	24236	26175	24841	26464	31218
Muscle work	7493	7596	7617	7421	7480	7689	7651	7791	7981	8158	8273	8081	8452	8518
Total useful work(TJ)	416247	470444	512442	585081	660204	717207	793540	844381	916090	981683	1020333	920066	1027842	1176146
Total exergy(TJ)	2467821	2706047	2875002	3255005	3484952	3715540	4009760	4257743	4614035	4904804	5052908	4390406	4914497	5278501
Final energy consumption(TJ)	2129833	2354373	2515282	2880685	3099493	3314032	3596372	3844656	4189091	4466973	4610059	3986923	4484198	4897378
Total exergy efficiency	0.17	0.17	0.18	0.18	0.19	0.19	0.20	0.20	0.20	0.20	0.20	0.21	0.21	0.22
Real GDP(B₩)	318971	356944	382036	419518	462955	491545	525199	573550	628442	676169	716213	677028	753590	820844
Population	41621690	42031247	42449038	42869283	43295704	43747962	44194628	44641540	45092991	45524681	45953580	46286503	46616677	47008111

Useful work category	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
High temperature heat	238198	244652	259527	262122	241901	259092	281166	317740	285530	346713	390455	404343	414553	440744
Medium temperature heat	161094	144367	127235	130140	130283	133138	136164	138458	127123	132719	126504	113054	117654	119623
Low temperature heat	128414	134511	139737	145083	153799	152528	154823	153177	151736	160996	162102	165098	168605	170241
Mechanical drive	613485	644665	668525	696405	704117	710801	746499	751454	788109	849476	878914	898848	915030	922594
Light	16860	16803	15876	14406	14022	12252	11257	12058	13046	13837	13346	12748	12082	11449
Other electric uses	32848	34549	35652	36946	38669	39397	40822	41258	40282	44164	46233	47370	47921	48053
Muscle work	8547	8597	8580	8724	8753	8831	8950	9156	9249	9522	9809	9775	9846	10399
Total useful work(TJ)	1199447	1228143	1255132	1293825	1291546	1316039	1379680	1423301	1415075	1557426	1627363	1651235	1685691	1723102
Total exergy(TJ)	5353079	5458888	5490454	5521278	5546304	5547481	5698202	5748271	5690682	6116854	6229189	6277468	6412535	6473036
Final energy consumption(TJ)	4969946	5079298	5108914	5166721	5197908	5196954	5344552	5394311	5331754	5737273	5845977	5890018	6017298	6066625
Total exergy efficiency	0.22	0.22	0.23	0.23	0.23	0.24	0.24	0.25	0.25	0.25	0.26	0.26	0.26	0.27
Real GDP(B₩)	857990	921759	948796	995286	1034338	1087876	1147311	1179771	1188118	1265308	1311893	1341967	1380833	1426972
Population	47370164	47644736	47892330	48082519	48184561	48438292	48683638	49054708	49307835	49554112	49936638	50199853	50428893	50746659

Table B.1: Korea’s Useful Work Consumption and Exergy Efficiency

Sector	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986
Industry	86719	95391	99147	117928	119290	137478	168772	172773	187250	187549	195718	193178	195285	206806
Transport	17120	17390	16714	17965	28311	31602	41677	33985	30634	33845	40331	43222	45683	54141
Commercial and public services	4626	4942	5169	5491	7060	9141	10691	10967	14939	15904	16291	19748	22453	26932
Residential	36259	37946	38682	41742	47365	48608	50942	54078	57734	57042	61080	68138	73504	77473
Others	1215	1259	1503	2051	2702	1918	1765	3368	2778	2869	3107	3019	3441	4130
Total	145940	156928	161215	185178	204728	228747	273846	275170	293336	297210	316527	327305	340367	369482

Sector	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Industry	231441	268347	293173	325401	380030	414474	459641	499824	535784	588230	615481	566065	625744	753082
Transport	69294	76559	86359	110529	122828	135699	154018	147513	163683	164764	170959	146484	164445	174832
Commercial and public services	33573	42257	51787	63131	74368	86247	100165	109446	117284	127972	135740	120706	133592	144216
Residential	78056	79389	75763	78635	71908	67009	62053	58019	62252	66336	70411	66976	76959	83193
Others	3883	3892	5360	7386	11069	13777	17663	29579	37088	34380	27742	19835	27102	20823
Total	416247	470444	512442	585081	660204	717207	793540	844381	916090	981683	1020333	920066	1027842	1176146

Sector	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Industry	761823	760881	773135	804306	795429	826546	878219	934238	900503	1021215	1095687	1108173	1136451	1178650
Transport	180717	193257	197128	199438	183064	181189	186884	172711	174198	176108	168999	176518	181121	186183
Commercial and public services	154978	163961	168507	172426	187763	174937	181041	181649	198359	211000	212421	214389	210651	205846
Residential	86655	96732	100941	102766	109129	122946	123254	125120	130975	137359	138145	140322	145690	140501
Others	15275	13311	15422	14890	16160	10420	10283	9582	11039	11743	12111	11833	11777	11921
Total	1199447	1228143	1255132	1293825	1291546	1316039	1379680	1423301	1415075	1557426	1627363	1651235	1685691	1723102

* Muscle work is included in the residential sector

Table B.2: Korea's Useful Work Consumption by Sectors

Energy source	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986
Coal	38936	44322	44220	50628	56563	59286	77050	88554	109875	113880	120286	115028	118892	120102
Oil	82465	84412	86329	99466	108676	123548	145425	133117	126607	123270	129598	139250	143451	162804
Natural gas	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Electricity	18432	22044	24249	28452	32857	39035	44465	46746	50118	53291	59745	65929	70972	79345
Renewables	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Heat	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Food	6107	6150	6418	6632	6632	6878	6907	6754	6735	6769	6897	7097	7052	7231
Others	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	145940	156928	161215	185178	204728	228747	273846	275170	293336	297210	316527	327305	340367	369482

Energy source	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Coal	126326	136213	134267	129026	140848	134454	145868	144739	152004	169421	173768	158493	164553	195890
Oil	191143	221456	254892	310346	357878	402176	443265	463708	488581	500038	490646	408000	459354	454361
Naturalgas	490	1201	2290	4047	6126	8328	13528	18326	26173	36471	50716	58585	74261	94868
Electricity	90795	103978	113376	129019	142531	158112	175994	201988	230001	258219	286261	275639	308062	383585
Renewables	0	0	0	5222	5341	6448	7233	6990	9954	7841	9114	9876	11289	18880
Heat	0	0	0	0	0	0	0	839	1396	1534	1555	1393	1871	20044
Food	7493	7596	7617	7421	7480	7689	7651	7791	7981	8158	8273	8081	8452	8518
Others	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	416247	470444	512442	585081	660204	717207	793540	844381	916090	981683	1020333	920066	1027842	1176146

Energy source	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Coal	201673	187474	184520	180602	157019	171179	187662	209852	176155	211364	233836	229258	224251	265693
Oil	439455	445309	437460	424104	407694	389872	389813	364590	356316	362720	345226	334272	342853	346939
Naturalgas	102763	108418	117009	129471	134157	138032	143214	157875	163650	195877	218619	240616	255690	229646
Electricity	409830	442122	469545	500049	532667	553421	589793	618052	650603	718934	760453	778401	789708	797294
Renewables	17998	16062	19539	23110	23603	27019	31039	35305	33845	35006	34817	36907	41276	47501
Heat	19180	20161	18479	27765	27653	27687	29211	28472	25257	24005	24604	22006	22067	25631
Food	8547	8597	8580	8724	8753	8831	8950	9156	9249	9522	9809	9775	9846	10399
Others	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	1199447	1228143	1255132	1293825	1291546	1316039	1379680	1423301	1415075	1557426	1627363	1651235	1685691	1723102

Table B.3: Korea’s Useful Work Consumption by Sources

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