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Estimation of energy use and CO_2 emission intensities by end use in South Korean apartment units based on in situ measurements

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ABSTRACT

The South Korean government is presently conducting a research project to provide measurement-based building energy consumption data for individual end uses, such as space heating, space cooling, domestic hot water (DHW), and other uses. From 2014 to 2019, energy consumption measurement systems for each end use were installed in sample buildings, and the measured data are being statistically processed with the objective of constructing an information system for energy use and CO_2 emission intensities by end use. This paper presents the statistical data for the site and primary energy use intensities (EUIs) and the CO_2 emission intensities by end use for the period of May 2017–April 2018; the data were obtained from measurements in 71 sample apartment units located in Seoul. The average site EUIs display the following order: space heating > electrical appliances > DHW > cooking > lighting > space cooling > air movement. Electrical appliances have the largest average primary EUI and CO_2 emission intensity. The average site EUIs exhibit the same order as those of the US Residential Energy Consumption Survey 2015 data: space heating > electrical appliances, etc. > DHW > space cooling.

1. Introduction

To achieve greenhouse gas reduction goals, many countries have recognized the importance of energy conservation in the building sector and are substantially strengthening building energy conservation policies by tightening design standards, promoting remodeling, imposing zero-energy construction requirements, etc. For these policies to produce actual results, it is necessary to not only secure technological and economic feasibility in the market but also provide energy information for the building sector that can be easily accessed by building users and policymakers to understand energy consumption characteristics. In particular, energy consumption information for each end use, such as space heating, space cooling, and lighting, which have different technical systems and are familiar to people, is useful because it can help establish concrete plans and policies for energy conservation.

Currently, building-sector energy information systems are being operated in many countries; major examples include the US Residential Energy Consumption Survey (RECS) [1] and Commercial Buildings Energy Consumption Survey (CBECS) [2]. These systems provide information on the energy consumption and energy use intensity (EUI) by building type (residential and commercial), building characteristics, and fuel type. This information is obtained by surveying sample buildings and collecting data from energy suppliers. In addition, these systems provide information on energy consumption and EUI by end use, which are estimated using statistical and engineering models. These data can be used to establish concrete plans for energy conservation.

The South Korean government operates the Korea Energy Statistics Information System (KESIS) and provides information on energy consumption by building type (residential, commercial, public, and large-scale), building characteristics, and fuel type. These data are collected via an energy census performed triennially for several types of sample buildings and an energy survey of sample housing units performed annually. In addition, for issuing energy assessment reports on individual buildings, an online portal called Green Together (GT) was constructed by collecting utility billing data from energy suppliers. GT provides information on energy consumption by fuel type in individual buildings and comparisons among similar buildings. However, these systems provide insufficient information on energy consumption and EUI by end use. Accordingly, the South Korean government is implementing a research project to provide measurement-based energy consumption data for each end use for the purpose of expanding building energy information that was mainly restricted to consumption data by fuel type. In the period from 2014 to 2019, energy consumption measurement systems for each end use were installed in sample

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buildings. The measured data are now being statistically processed, and an information system is being constructed to provide energy use and CO_2 emission intensity data by end use. This project has two target building types: office buildings and apartments; the latter are typical examples of residential buildings in South Korea.

The aim of this study is to present statistical data for the site and primary EUIs and CO_2 emission intensities by end use for the period of May 2017–April 2018, as obtained from the data collected at 71 sample apartment units located in Seoul. The current status of information systems and previous studies related to residential energy consumption by end use were investigated. The sample design for energy consumption measurements, energy consumption classifications and definitions by end use, and measurement and data collection methods, which were reported in the authors' previous studies [3–5], are summarized. Field surveys were performed on 71 sample apartment units in 16 apartment complexes located in Seoul, in which the abovementioned energy consumption measurement systems were installed during the period from 2014 to 2016. The construction, technical system, and usage category characteristics were investigated, and energy consumption measurement data by end use were collected. The site energy consumption results by end use for each sample household over the period between May 2017 and April 2018 were determined, and conversion factors were applied to obtain the primary energy consumption and CO_2 emissions by end use. These values were divided by the floor area of each household to obtain the intensities. Then, statistical values such as the averages, percentiles, and standard deviations were calculated to understand the intensity distribution characteristics of all 71 sample households. The magnitudes and trends of the monthly average site EUIs by end use were also analyzed, and the average site EUIs by end use were compared with the RECS 2015 data, i.e., the most recent RECS data.

2. Information systems and previous studies related to residential energy consumption by end use

2.1. Information systems in the United States and Europe

The RECS is a quadrennial survey performed in the US for a national representative sample of housing units and is administered by the US Energy Information Administration (EIA). The EIA is the statistical and analytical agency within the US Department of Energy and was established in 1977 as the single federal government authority for all energy-related statistics. The first RECS was conducted in 1978. The survey was then conducted annually until 1984, when a triennial cycle was initiated. Since 1993, the survey has been conducted on a quadrennial cycle. The RECS is the only national household energy survey performed in the US [6].

For data acquisition, specially trained interviewers collect energy characteristics regarding each housing unit, usage patterns, and household demographics. This information is combined with data from the energy suppliers associated with these homes to estimate energy costs and usage regarding various end uses [1,7]. Before 2015, statistical regression models were used in the RECS to disaggregate the energy consumption for a given home across five end uses: space heating, water heating, air conditioning, refrigerators, and other. In the 2015 study, the EIA transitioned to engineering models, which can incorporate more equipment information and usage behaviors from the RECS household data, as well as information from research and data on equipment specifications. Hence, estimates of device energy consumption in homes were produced [8]. The RECS 2015 data, which are the most recent data, provide the total site energy consumption and expenditures in terms of both end use and fuel type, as well as the average site energy consumption and expenditures per household in terms of end use and fuel type, for housing in each region of the US. In addition to the five end use categories, fuel type is divided into four categories: electricity, natural gas, propane, and fuel oil and kerosene. Moreover, detailed consumption and expenditure estimates for more than 20 new end uses are included in the RECS 2015 data. For the electricity category, consumption and expenditure estimates are categorized for 25 end uses (space heating, air handlers for heating, air conditioning, air handlers for cooling, etc.). For natural gas, these data are categorized according to six end uses (space heating, water heating, clothes dryers, cooking, etc.). For propane, data are categorized for four end uses (space heating, water heating, clothes dryers, and cooking).

The European Union (EU) collects household energy consumption data in terms of end use for each member state in accordance with Regulation (EC) No. 1099/2008 on energy statistics, as amended by Commission Regulation (EU) No. 431/2014. The associated statistical information is provided by the European Statistical Office, Eurostat. Eurostat is a directorate general of the European Commission (EC) and is located in Luxembourg. The main responsibilities of this organization are to provide EU institutions with statistical information and to promote the harmonization of statistical methods across its member states and candidates for accession, as well as European Free Trade Association (EFTA) countries. The organizations in the different countries that cooperate with Eurostat are summarized under the European Statistical System. The information provided by Eurostat includes the total energy consumption and ratio by end use and fuel type for all member states, as well as the energy consumption ratio by end use and fuel type for each member state. The end uses are divided into six categories: space heating, space cooling, water heating, cooking, lighting and appliances, and other. Fuel types are divided into six categories: electricity, derived heat, gas, solid fuels, oil and petroleum products, and renewables and wastes [9]. The data acquisition methods vary among member states and can be broadly categorized as surveys, use of administrative data, modeling, and in situ measurements. Table 1 lists the data acquisition methods of selected member states [10]. Each member state also provides related information independently. For example, the UK provides domestic energy consumption data by end use and fuel from 1990 to 2017 as a national statistic as of July 2018; these data are updated annually. The end uses are divided into five categories: space heating, water heating, cooking, lighting, and appliances. Fuel types are divided into six categories: solid fuels, gas, electricity, oil, heat sold, and bioenergy and wastes [11].

Table 1
Data acquisition methods of energy consumption by end use in Europe.

Data acquisition method		Austria	Germany	Nether-lands	Poland	Slovenia	Spain	United Kingdom
Surveys	Survey of businesses							O
	Survey of consumers	O	O	O	O	O	O	O
Use of administrative data				O			O	O
Modeling		O		O		O		O
In situ measurements		O					O	
Integrated approach		O		O		O	O	O

2.2. Previous studies

Chen et al. [12] developed a statistical method to investigate energy consumption in the Chinese residential building sector to determine the actual residential energy consumption characteristics and provide data support for building energy efficiency refinements in China. Hu et al. [13] investigated and analyzed the actual conditions of residential energy consumption in four Chinese cities to ascertain the important factors that influence annual energy consumption. Furthermore, Chen et al. [14] compared the energy use characteristics of old and new residential buildings in Shanghai to analyze the factors that lead to differences in energy consumption between high- and low-energy use family groups for space heating and cooling. Bohlmann et al. [15] analyzed the energy characteristics of the South African residential sector considering the energy use profiles of cooking, lighting, and heating. Other characteristics, such as the geographical distribution and demographics, were also considered. In addition, Carpino et al. [16] created and administered a questionnaire to collect data regarding heating, cooling, lighting, appliance, and domestic hot water (DHW) usage and to obtain the typical occupancy profiles of residential buildings in southern Italy. Wu et al. [17] presented a systematic overview of rural household energy consumption in China from 1985 to 2013 and quantified and illustrated rural household energy consumption patterns using the Chinese Residential Energy Consumption Survey (CRECS, 2013). Energy consumption was classified into seven types of energy and five types of end uses. Stoppok et al. [18] compared household energy consumption data from Kenya, Germany, and Spain, considering end uses such as cooling, hot water, lighting, cooking, and others. Wan et al. [19] conducted surveys to obtain information on the building design and energy characteristics by end use of high-rise residential buildings in Hong Kong, including annual energy use for air conditioning and water heating in residential units. Attia et al. [20] reported the results of a field survey on residential apartment buildings in Egypt and presented details of building models, including the energy use patterns and profiles for lighting, plugs, cooking, DHW, and mechanical cooling (electric fans and air conditioners).

3. Sample design, energy consumption measurements, and data collection

3.1. Sample design

In South Korea's Building Act Enforcement Decree [21], apartments are defined as multiunit dwellings of five stories or more. These are typical residential buildings accounting for 58% of the total residential floor area in South Korea [22]. In South Korea, apartments are built in a relatively standardized form, and their construction and technical system characteristics are similar. The space heating systems employed in almost all apartments are floor radiant heating systems that use hot water. The space heating and DHW heat sources are district heating or hot water boilers installed in individual households. The fuel of hot water boiler is liquefied natural gas supplied from the city gas pipe network. No central systems are used for space cooling. Air conditioners are often individually installed by the occupants.

Table 2 presents the sample design results [23] for the energy consumption measurements by end use. The installation of energy consumption measurement systems by end use is time consuming and costly; therefore, the locations of the apartments to be evaluated were first selected for a statistically significant sample design within a given budget range. South Korea is divided by climate conditions into the central, southern, and Jeju regions. According to government statistical data [24], the central region accounts for a vastly larger percentage of residential building floor area than the southern and Jeju regions. Thus, apartments in Seoul were targeted, as Seoul is a representative city of the central region. After the completion of the research project, the government will evaluate the usefulness of the developed information system and determine whether to expand it to the southern and Jeju regions.

Table 2
Sample design of the apartment units for energy consumption measurements by end use.

Completion year	Heat source type	Supplied floor area	Number of sample units
1993 or earlier	District heating	Less than 66.0 m^2	11
		Less than 115.5 m^2	11
		115.5 m^2 or more	11
	Individual heating	Less than 66.0 m^2	11
		Less than 115.5 m^2	11
		115.5 m^2 or more	12
2003 or earlier	District heating	Less than 66.0 m^2	11
		Less than 115.5 m^2	11
		115.5 m^2 or more	11
	Individual heating	Less than 66.0 m^2	11
		Less than 115.5 m^2	11
		115.5 m^2 or more	11
2004 or later	District heating	Less than 66.0 m^2	12
		Less than 115.5 m^2	11
		115.5 m^2 or more	11
	Individual heating	Less than 66.0 m^2	11
		Less than 115.5 m^2	11
		115.5 m^2 or more	11
Total	–	–	200

Table 3
Measurement system installation schedule for sampled apartment units.

Year	2014	2015	2016	2017	2018	2019	Total
Number of sample units	2	48	30	55	50	15	200

The selected stratification variables for the sample design were the completion year, type of heat source for space heating and DHW, and unit's floor area. Considering the time periods in which insulation design standards were greatly strengthened in the past, the completion year stratification levels were classified as 1993 or earlier, 2003 or earlier, and 2004 or later. The heat source stratification levels were classified as district and individual heating. The unit's floor area stratification levels were based on the supplied floor area (exclusive use floor area + shared floor area assigned to the unit); this index is familiar to South Korean citizens and widely used. Using government data [25], the levels were classified as less than 66.0 m^2, less than 115.5 m^2, and 115.5 m^2 or more. The Neyman allocation method was used to design the samples with a confidence level of 95% and a tolerance of 20% for the above stratification variables and levels. In accordance with the research project plan, measurement systems were installed in all sample units over a six-year period that began in 2014. Table 3 presents the measurement system installation schedule.

3.2. Classifications and definitions of energy consumption by end use

The classifications and definitions of energy consumption by end use, as reported in the authors' previous studies [3 – 5], are listed in Table 4. Here, energy consumption is the energy delivered to the technical system, i.e., the energy consumption billed by the energy suppliers.

3.3. Methods for energy consumption measurements and data collection by end use

Methods for measuring energy consumption by end use, as reported in the authors' previous studies [3 – 5], are summarized in Tables 5 and 6. With regard to the research project men-

Table 4
Classifications and definitions of energy consumption by end use in apartment units.

Classification	Definition	
Space heating	The energy consumption of the main space heating system, including the heat source and pump	
	District heating	• The primary heat input to the apartment complex heat exchanger, corresponding to the heat consumed for space heating of the unit; this reflects the heat loss of the heat supply system from the heat exchanger to the unit entrance • The electricity consumption, per unit, of the apartment complex space heating hot water circulation pump (electricity consumption of the pump x floor area of the unit / total floor area of the units served by the pump)
	Individual heating	• The boiler gas consumption for space heating • The boiler electricity consumption for operation (control, etc.)
Space cooling	The electricity consumption of the air conditioner, which is the main space cooling system	
Domestic hot water (DHW)	The energy consumption of the main DHW system, including the heat source and pump	
	District heating	• The primary heat input to the apartment complex heat exchanger, corresponding to the heat consumed for DHW of the unit; this reflects the heat loss of the heat supply system from the heat exchanger to the unit entrance • The electricity consumption, per unit, of the apartment complex DHW circulation pump (electricity consumption of the pump x floor area of the unit / total floor area of the units served by the pump)
	Individual heating	• The boiler gas consumption for DHW • The boiler electricity consumption for operation (control, etc.)
Lighting	The electricity consumption of the main lighting system with a separate branch circuit	
Air movement	The electricity consumption of the ventilation unit and exhaust fan	
Electrical appliances	• The remaining electricity consumption obtained by subtracting the electricity consumption for other uses from the total electricity consumption • This corresponds to unclassified total electricity consumption via power outlets	
Cooking	The energy consumption of the main cooking system, including gas and electric cook-tops	

Table 5
Measured items, measurement instruments, and measurement locations for energy consumption measurements by end use in the case of district heating.

Classification	Measured item	Measurement instrument	Measurement location	
Unit	Space heating	Heat of space heating hot water	Calorimeter	Space heating hot water pipe at unit entrance
	Space cooling	Air conditioner electricity consumption	Watt-hour meter or smart plug	Electricity distribution board or power outlet
	DHW	DHW flow rate	Flowmeter	DHW pipe at unit entrance
	Lighting	Main lighting system electricity consumption	Watt-hour meter	Electricity distribution board
	Air movement	The electricity consumption for air movement was not measured because of its small scale. This factor was estimated based on the rated fan power and interview data concerning operating schedules.		
	Electrical appliances	Total electricity consumption in unit	Watt-hour meter	Electricity distribution board
	Cooking	Gas flow rate of gas cook-top	Flowmeter	Gas pipe of gas cook-top
		Electricity consumption of electric cook-top (if present)	Watt-hour meter or smart plug	Electricity distribution board or power outlet
Complex	Space heating hot water circulation	Pump electricity consumption	Watt-hour meter	Dependent on site conditions
	DHW circulation	Pump electricity consumption	Watt-hour meter	Dependent on site conditions
	Temperature difference of DHW	Supplied hot water temperature [a]	Thermometer	Heat exchanger pipe
		City-water temperature [a]	Thermometer	Heat exchanger pipe

[a]This temperature is used to obtain the DHW heat along with the flow rate measured at the unit level.

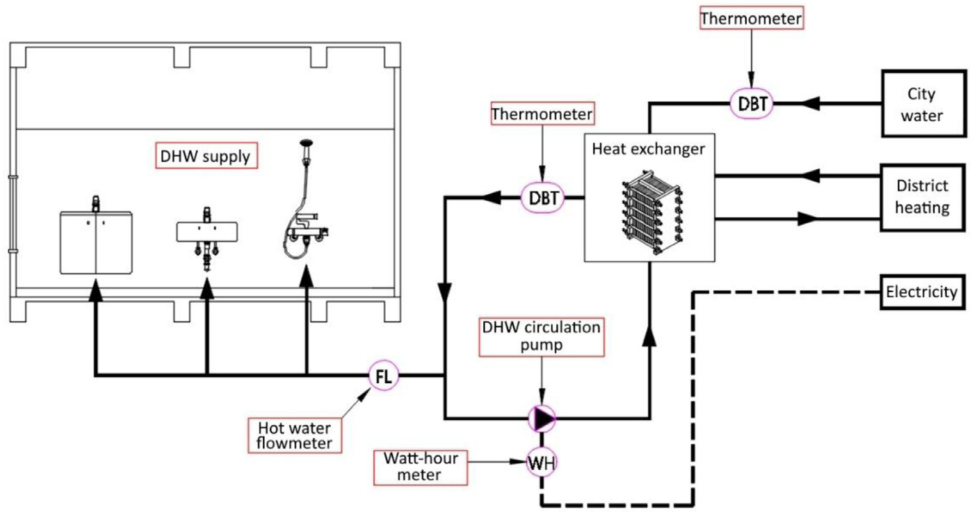
Table 6
Measured items, measurement instruments, and measurement locations for energy consumption measurements by end use in the case of individual heating.

Classification	Measured item	Measurement instrument	Measurement location	
Unit	Space heating + DHW + cooking	Gas flow rate for boiler and gas cook-top	Flowmeter	Main gas pipe
	Space heating + DHW	Gas flow rate for boiler	Flowmeter	Boiler gas pipe
		Boiler electricity consumption for operation	Watt-hour meter or smart plug	Electricity distribution board or power outlet
	Space heating	Heat of space heating hot water (measurement of one item from space heating hot water and DHW)	Calorimeter	Space heating hot water distributor pipe
	Space cooling	Air conditioner electricity consumption	Watt-hour meter or smart plug	Electricity distribution board or power outlet
	DHW	Heat of DHW (measurement of one item from space heating hot water and DHW)	Calorimeter	Boiler DHW pipe
	Lighting	Main lighting system electricity consumption	Watt-hour meter	Electricity distribution board
	Air movement	The electricity consumption for air movement was not measured because of its small scale. This factor was estimated based on the rated fan power and interview data concerning operating schedules.		
	Electrical appliances	Total electricity consumption in a unit	Watt-hour meter	Electricity distribution board
	Cooking	Electricity consumption of electric cook-top (if present)	Watt-hour meter or smart plug	Electricity distribution board or power outlet

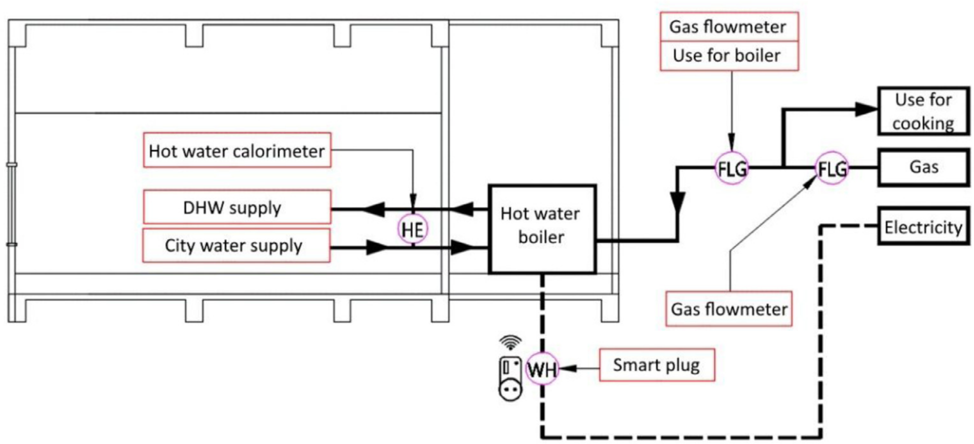
Table 7
Details of the measurement instruments.

Instrument	Model name	Specifications	Website	Photograph
Hot water calorimeter	WDHM-15/20	• Range: 0~90 °C • Maximum value: 999,999 kWh • Minimum value: 0.01 kWh • Size: 102 × 102 × 54 mm	wzit.co.kr	
Hot water flowmeter	SD-15	• Passed the static magnetic field test • Certified hygiene & security • Diameter: 15 mm/20 mm • Error: ±2.0% • Minimum measurement unit: 0.0001 m^3	dsmeters.co.kr	
Gas flowmeter	G1.6, G2.5	• Maximum operating pressure: 10 kPa • Maximum flowrate: 4.0 m^3/h • Minimum flowrate: 0.025 m^3/h • Communication method: Pulse/MM-BUS • Size: 164 × 221 × 134 mm	dsmeters.co.kr	
Watt-hour meter	ANYPA-Multi100	• Measurement voltage: 220/380 V • Measurement current: ~1000A • Error: ±0.5% • Communication method: 232/485/TCP/IP, LPWA IoT/ 900Mhz RF	cncinst.co.kr	
Smart plug	ANYPA-SPG100	• 1 bulb socket type current measurement • Measurement voltage: 220 V • Measurement current: 15A • Communication method: LPWA IoT/ 900Mhz RF • Error: ±0.5% • Size: 58 × 117 × 78 mm	cncinst.co.kr	
Room air thermo-hygrometer	ANYPA-STH100	• Range: −40~123.8 °C / 0~100%RH • Error: ±0.4 °C / ±3%RH • Communication method: LPWA IoT/ 900Mhz RF • Size: 67 × 92 × 28 mm	cncinst.co.kr	

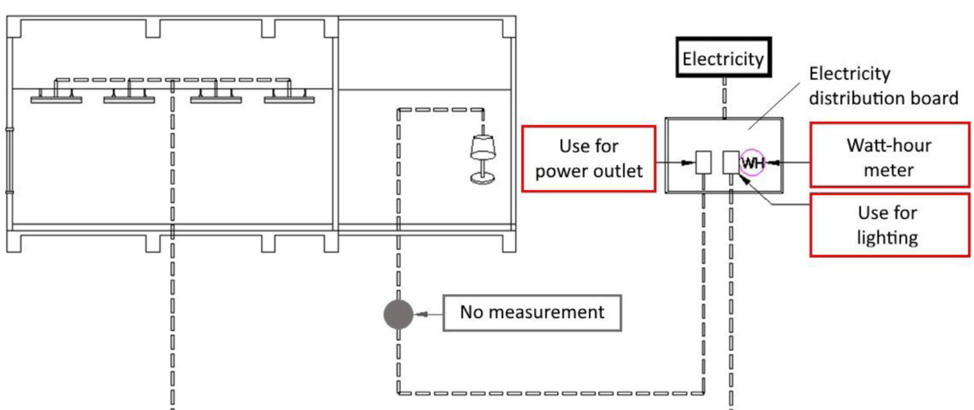
tioned above, the measurement system installation program was announced by the Korea Energy Agency, which is a public organization. The bidding companies were evaluated, and measurement system installation companies were selected. The selected companies then recruited sample households and installed measurement systems according to the methods detailed in Tables 5 and 6. Table 7 presents the details of the measurement instruments and Fig. 1 shows the diagram examples for measuring energy consumption by end use. Table 8 shows photographs of the sample apartment complexes and units. To ensure stability and ease of management, the measurement data were primarily stored on the server of each company and secondarily stored on the Korea Energy Agency integrated server, as shown in Fig. 2. The secondarily stored measurement data were monitored continuously, and missing and abnormal data were processed according to pre-defined principles.



(a) DHW in the case of district heating



(b) Space heating + DHW + cooking, space heating + DHW, and DHW in the case of individual heating



(c) Lighting

Fig. 1. Diagram examples for measuring energy consumption by end use
(a) DHW in the case of district heating
(b) Space heating + DHW + cooking, space heating + DHW, and DHW in the case of individual heating
(c) Lighting.

Table 8
Photographs of the sample apartment complexes and units.

4. Calculation and analysis of statistical values for energy consumption and CO_2 emission intensities by end use

4.1. Sample apartment unit characteristics

Field surveys were performed on 71 sample apartment units in 16 apartment complexes located in Seoul, in which measurement systems were installed during the period from 2014 to 2016. The sample apartment unit distributions according to the stratification variables and levels in the sample design (refer to Table 2) are presented in Table 9. The construction, technical system, and usage category characteristics of sample units are presented in Tables 10–12.

The sample unit construction category characteristics in Table 10 indicate that 46% and 54% of the buildings were corridor type and hall type, respectively, with most of the units being located in the center of the middle floor (48%) and 38% located around the perimeter of the middle floor. Most units were southeast oriented (42%), with 37% being southwest oriented. Almost all South Korean apartment units have additional windows installed on the outdoor side of the balcony so that the balcony is converted into an unheated indoor space. There are also cases in which the windows between the balcony and heated indoor space have been removed, thereby removing the balcony and increasing the effective indoor floor area, which is allowed by law. The balcony can act as a thermal buffer zone between the outdoors and the heated indoor space. When the balcony is removed, the space heating and cooling energy consumption can increase. The percentage of units without balconies was 34%; thus, units with balconies were more common. Most units had 3 bedrooms and 1 bathroom, accounting for 61% and 62% of all units, respectively.

The technical system characteristics for the sample units listed in Table 11 indicate that 30% and 70% of the households with individual heating employ condensing and non-condensing boilers, respectively. Most units (70%) had boiler efficiencies of less than 87%. With regard to air conditioners, most units (52%) had one indoor unit, and a total power of outdoor units of less than

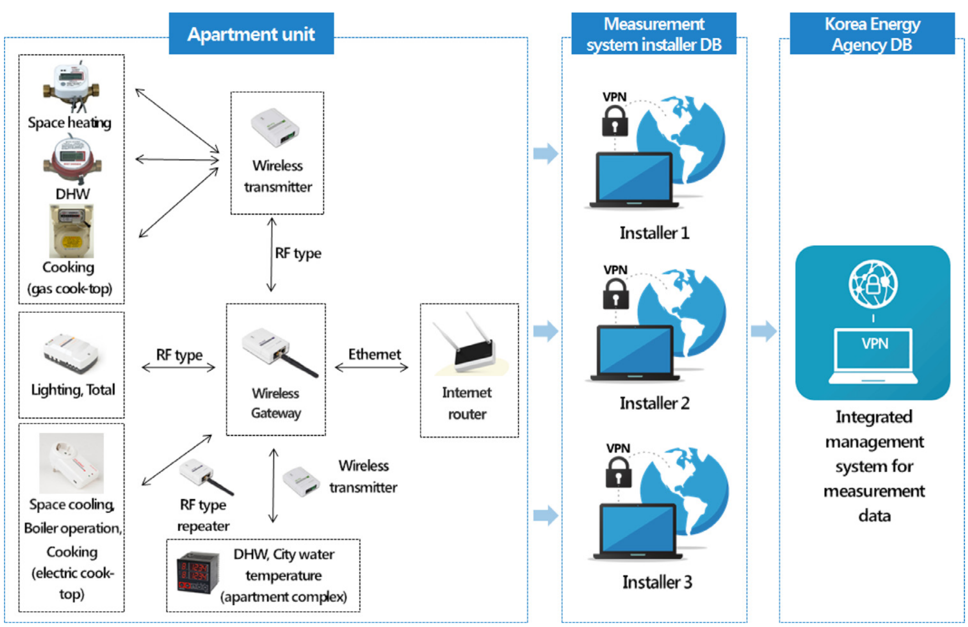


Fig. 2. Diagram of the measurement data acquisition system.

Table 9
Distributions of the sample apartment units.

Completion year	Number of sample units	Heat source type	Number of sample units	Supplied floor area (m^2)	Number of sample units	Exclusive use floor area (m^2)	Number of sample units
1993 or earlier	22 (31%)	District heating	21 (30%)	Less than 66.0	12 (17%)	Less than 60.0	17 (24%)
2003 or earlier	19 (27%)	Individual heating	50 (70%)	Less than 115.5	42 (59%)	Less than 85.0	21 (30%)
2004 or later	30 (42%)	–	–	115.5 or more	17 (24%)	85.0 or more	33 (46%)
Total	71 (100%)	Total	71 (100%)	Total	71 (100%)	Total	71 (100%)
Max.	2012	–	–	Max. (m^2)	172.6	Max. (m^2)	136.7
Min.	1985	–	–	Min. (m^2)	36.5	Min. (m^2)	26.4
Avg.	1999	–	–	Avg. (m^2)	97.9	Avg. (m^2)	78.9

Table 10
Construction characteristics of the sample apartment units.

Plan type of buildings	Number of sample units	Location	Number of sample units	Orientation	Number of sample units
Corridor type	33 (46%)	First floor, center	3 (4%)	East	1 (1%)
Hall type	38 (54%)	First floor, side	2 (3%)	Southeast	30 (42%)
–	–	Middle floor, center	34 (48%)	South	9 (13%)
–	–	Middle floor, side	27 (38%)	Southwest	26 (37%)
–	–	Top floor, center	4 (6%)	West	5 (7%)
–	–	Top floor, side	1 (1%)	–	–
Total	71 (100%)	Total	71 (100%)	Total	71 (100%)
Balcony removal	Number of sample units	Number of bedrooms	Number of sample units	Number of bathrooms	Number of sample units
Yes	24 (34%)	1	5 (7%)	1	44 (62%)
No	47 (66%)	2	11 (15%)	2	27 (38%)
–	–	3	43 (61%)	–	–
–	–	4 or more	12 (17%)	–	–
Total	71 (100%)	Total	71 (100%)	Total	71 (100%)
–	–	Max.	5.0	Max.	2.0
–	–	Min.	1.0	Min.	1.0
–	–	Avg.	2.9	Avg.	1.4

Table 11
Technical system characteristics of the sample apartment units.

Boiler type for individual heating	Number of sample units	Rated boiler efficiency for individual heating (%)	Number of sample units	Number of air conditioner's indoor units	Number of sample units	Sum of rated power of air conditioner's outdoor units (kW)	Number of sample units
Condensing	15 (30%)	Less than 87	35 (70%)	None	13 (18%)	None	13 (18%)
Non-condensing	35 (70%)	87 or more	15 (30%)	1	37 (52%)	Less than 2	31 (44%)
–	–	–	–	2	18 (25%)	Less than 3	23 (32%)
–	–	–	–	3 or more	3 (4%)	3 or more	4 (6%)
Total	50 (100%)	Total	50 (100%)	Total	71 (100%)	Total	71 (100%)
–	–	Max. (%)	91.2	Max.	4.0	Max. (kW)	4.0
–	–	Min. (%)	81.6	Min.	0.0	Min. (kW)	0.5
–	–	Avg. (%)	84.4	Avg.	1.2	Avg. (kW)	1.9

Lighting power density (W/m^2)	Number of sample units	Always-on electrical appliance power density [a] (W/m^2)	Number of sample units	Intermittent-on electrical appliance power density [b] (W/m^2)	Number of sample units
Less than 3	7 (10%)	Less than 2	25 (35%)	Less than 6	15 (21%)
Less than 6	16 (23%)	Less than 4	27 (38%)	Less than 12	26 (37%)
Less than 9	19 (27%)	4 or more	19 (27%)	Less than 18	14 (20%)
Less than 12	13 (18%)	–	–	18 or more	16 (23%)
12 or more	16 (23%)	–	–	–	–
Total	71 (100%)	Total	71 (100%)	Total	71 (100%)
Max. (W/m^2)	21.4	Max. (W/m^2)	12.2	Max. (W/m^2)	53.6
Min. (W/m^2)	1.4	Min. (W/m^2)	1.0	Min. (W/m^2)	1.7
Avg. (W/m^2)	8.4	Avg. (W/m^2)	3.4	Avg. (W/m^2)	13.1

[a] refrigerator, kimchi refrigerator, water purifier, etc.
[b] television, computer, washing machine, etc.

2 kW constituted the most common value (44%), and 2 kW or more but less than 3 kW constituted a relatively high percentage at 32%. The average lighting power density was 8.4 W/m^2, and the average power densities for always-on (refrigerator, etc.) and intermittent-on (television, etc.) electrical appliances were 3.4 W/m^2 and 13.1 W/m^2, respectively. The density was based on the exclusive use floor area of each sample unit.

The sample unit usage category characteristics in Table 12 show that many units had four or more occupants, and households with occupant densities of 0.02 person/m^2 or more but less than 0.04 person/m^2 constituted the majority of units. For the space heating set-point temperature, high percentages of units had temperature settings around 24 °C. A space heating period from November to March (five months) and average space heating of less than twelve hours per day were reported for most units. Most households reported a space cooling period using an air conditioner from July to August (two months) and less than four average space cooling hours daily. The percentage of units without an air conditioner was high at 18%. Most households had at least five faucets for DHW (tub, shower, basin, sink, washing machine, etc.) and less than three daily average DHW usage hours in winter. The daily average DHW usage hours in winter were determined from the daily average number of uses for each faucet (use/faucet•day) for DHW on weekdays and weekends, the usage time for individual use (time/use), and the number of faucets for DHW. For the daily average lighting hours in the living room, 3 h or more but less than 6 h and 6 h or more but less than 9 h constituted the majority of units, accounting for 39% and 38% of all units, respectively.

4.2. Intensity calculation and statistical processing method

The site energy consumption by end use for each sample unit for the one-year period from May 2017 to April 2018 was measured. Then, the conversion factors for the fuel types presented in

Table 12
Usage characteristics of the sample apartment units.

Number of occupants	Number of sample units	Occupant density ($person/m^2$)	Number of sample units	Space heating set-point temperature (°C)	Number of sample units	Space heating period (month)	Number of sample units
1	2 (3%)	Less than 0.02	6 (8%)	Less than 20	4 (6%)	2 or less	4 (6%)
2	22 (31%)	Less than 0.04	33 (46%)	Less than 24	29 (41%)	4 or less	13 (18%)
3	17 (24%)	Less than 0.06	24 (34%)	Less than 28	32 (45%)	6 or less	48 (68%)
4 or more	30 (42%)	0.06 or more	8 (11%)	28 or more	6 (8%)	More than 6	6 (8%)
Total	71 (100%)	Total	71 (100%)	Total	71 (100%)	Total	71 (100%)
Max.	5.0	Max. ($person/m^2$)	0.10	Max. (°C)	30.0	Max.(month)	7.5
Min.	1.0	Min. ($person/m^2$)	0.01	Min. (°C)	18.0	Min. (month)	1.0
Avg.	3.1	Avg. ($person/m^2$)	0.04	Avg. (°C)	23.6	Avg. (month)	4.7

Daily average space heating hours (hour)	Number of sample units	Space cooling period using air conditioner (month)	Number of sample units	Daily average space cooling hours using air conditioner (hour)	Number of sample units
Less than 4	18 (25%)	None	13 (18%)	None	13 (18%)
Less than 8	14 (20%)	1 or less	22 (31%)	Less than 4	32 (45%)
Less than 12	25 (35%)	2 or less	33 (46%)	Less than 8	13 (18%)
12 or more	14 (20%)	More than 2	3 (4%)	8 or more	13 (18%)
Total	71 (100%)	Total	71 (100%)	Total	71 (100%)
Max. (hour)	24.0	Max. (month)	3.0	Max. (hour)	24.0
Min. (hour)	1.0	Min. (month)	0.0	Min. (hour)	0.0
Avg. (hour)	8.4	Avg. (month)	1.6	Avg. (hour)	4.2

Number of faucets for DHW	Number of sample units	Daily average DHW usage hours in winter (hour)	Number of sample units	Daily average lighting hours in living room (hour)	Number of sample units
Less than 5	13 (18%)	Less than 1	11 (15%)	Less than 3	14 (20%)
Less than 7	27 (38%)	Less than 3	34 (48%)	Less than 6	28 (39%)
7 or more	31 (44%)	Less than 5	15 (21%)	Less than 9	27 (38%)
–	–	5 or more	11 (15%)	9 or more	2 (3%)
Total	71 (100%)	Total	71 (100%)	Total	71 (100%)
Max.	9.0	Max. (hour)	8.7	Max. (hour)	12.0
Min.	3.0	Min. (hour)	0.1	Min. (hour)	1.0
Avg.	5.8	Avg. (hour)	2.7	Avg. (hour)	5.0

Table 13
Primary energy conversion factors for site energy consumption by fuel.

Classification	Primary energy conversion factor
Electricity	2.75
Gas	1.10
District heating	0.728

Tables 13 [26] and 14 [27,28] were applied to obtain the primary energy consumption and CO_2 emission results by end use. These values were divided by the exclusive use floor area of each sample unit to obtain the intensities.

Statistical values were calculated to clarify the intensity distribution characteristics of all 71 sample units. To reduce the effects of notably large or small intensities in certain samples, the top and bottom 10% of each intensity data set were excluded from the calculation of the statistical values. The average, median, and mode can be used to represent intensity distribution characteristics. Because the sample design in this study focused on estimating the average with a certain level of tolerance, the average value was used as the representative value. Furthermore, it is difficult to concretely understand the intensity distribution characteristics based solely on the average value; therefore, the maximum value, minimum value, percentiles, and standard deviation were also calculated.

Table 14
CO_2 emission conversion factors for site energy consumption by fuel.

Classification	CO_2 emission conversion factor [a]	Remark
Electricity	0.46625 $kgCO_2/kWh$	Average of two years (2007, 2008)
Liquefied natural gas	56,236 $kgCO_2/TJ$	–
District heating	59,685 $kgCO_2/TJ$	Average of heat-only and cogeneration systems

[a]Total emissions of each greenhouse gas (CO_2, CH_4, N_2O) obtained as CO_2 equivalents. CO_2 equivalents of CH_4 and N_2O emissions are obtained by applying global warming potential, which indexes the effect of each greenhouse gas on global warming compared to CO_2 (CO_2: 1, CH_4: 21, N_2O: 310).

4.3. Analysis of statistical values for energy consumption and the CO_2 emission intensities by end use

4.3.1. Site EUIs by end use

The statistical values for the site EUIs by end use are presented in Table 15. A box plot graph of these values is shown in Fig. 3. The average site EUIs by end use exhibited the following order: space heating > electrical appliances > DHW > cooking > lighting > space cooling > air movement. The space heating, electrical appliances, and DHW values were large at 83.5, 41.5,

Table 15
Statistics for site EUIs by end use (kWh/m^2•year).

Classification		Space heating	Space cooling	DHW	Lighting	Air movement	Electrical appliances	Cooking	Total
Average (Representative value)		83.5	1.5	24.8	5.4	0.4	41.5	11.4	141.2
Maximum		147.9	3.6	52.0	10.8	1.3	60.6	26.9	227.8
Minimum		29.8	0.3	4.5	2.6	0.0	23.8	4.2	56.6
Percentile	10th	38.0	0.5	12.6	2.7	0.1	26.0	5.2	78.4
	25th	55.5	0.7	14.3	3.5	0.2	32.6	8.8	107.3
	50th	79.4	1.3	23.1	4.6	0.3	41.4	11.1	138.4
	75th	112.2	2.0	35.0	7.4	0.6	49.1	13.7	176.0
	90th	127.7	3.1	41.4	8.4	0.8	58.7	16.2	205.8
Standard deviation		35.5	1.0	12.8	2.3	0.3	11.8	5.0	48.7
Ratio based on average		49.5%	0.9%	14.7%	3.2%	0.2%	24.6%	6.8%	–

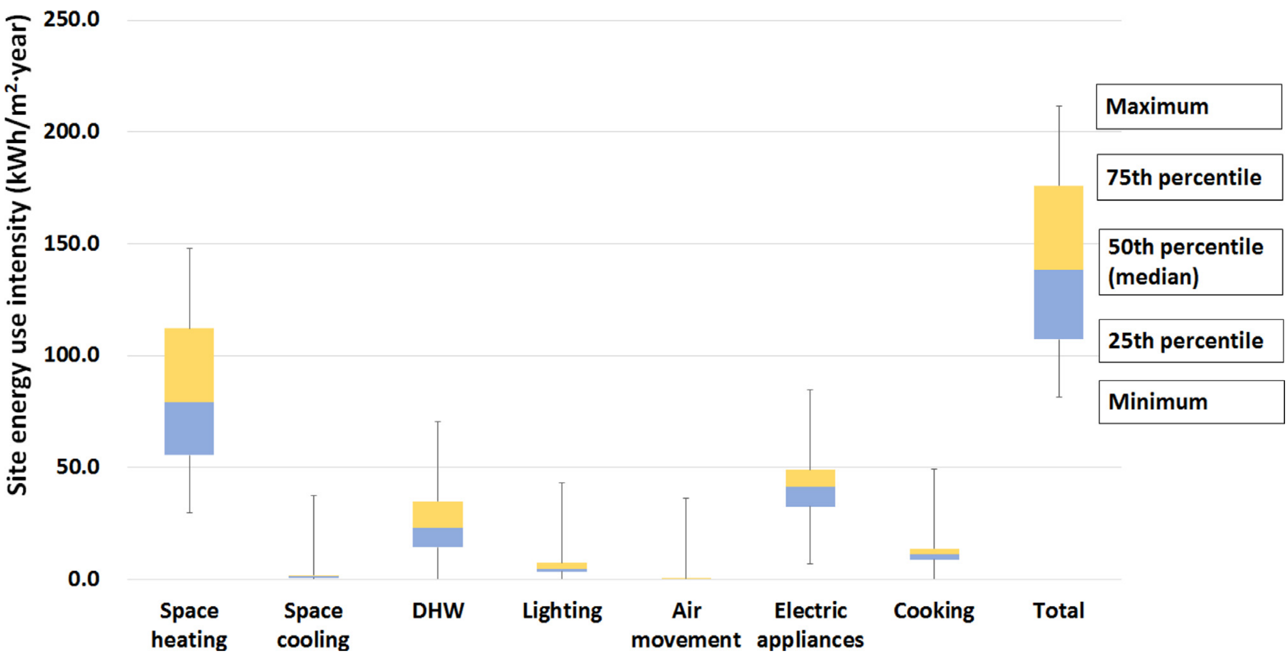


Fig. 3. Box plot of site EUIs by end use (kWh/m^2•year).

and 24.8 kWh/m^2•year, respectively; those for cooking and lighting were 11.4 and 5.4 kWh/m^2•year, respectively; and those for space cooling and air movement were small at 1.5 and 0.4 kWh/m^2•year, respectively. Regarding the percentages of the average site EUIs by end use, those for space heating, electrical appliances, and DHW were 49.5, 24.6, and 14.7%, respectively, and those for cooking and lighting were 6.8 and 3.2%, respectively. Hence, the average site EUI for space heating is overwhelmingly the largest, that for electrical appliances corresponds to approximately half that for space heating and that for DHW is slightly more than half that for electrical appliances. Furthermore, the standard deviations of the site EUIs for space heating, DHW, and electrical appliances were relatively large. This result indicates that the differences in the site EUIs for these end uses were large between sample units compared to the differences for other end uses. The average total site EUI for the sample units was 141.2 kWh/m^2•year. This value is the average of the total site EUIs for each sample unit and not the total of the average site EUIs per end use.

4.3.2. Primary EUIs by end use

The statistical values for the primary EUIs by end use are presented in Table 16, and a box plot graph of these values is shown in Fig. 4. The average primary EUIs by end use exhibited the following order: electrical appliances > space heating > DHW > lighting > cooking > space cooling > air movement. The values for the electrical appliances, space heating, and DHW were large at 119.7, 92.1, and 28.1 kWh/m^2•year, respectively; those for lighting and cooking were 15.3 and 14.1 kWh/m^2•year, respectively; and those for space cooling and air movement were small at 4.3 and 1.1 kWh/m^2•year, respectively. Regarding the percentages of the average primary EUIs by end use, those for electrical appliances, space heating, and DHW were 43.6, 33.5, and 10.2%, respectively, and those for lighting and cooking were 5.6 and 5.1%, respectively. Compared to the site EUI results, the order of space heating and electrical appliances and the order of lighting and cooking were reversed for the primary EUIs because the primary energy conversion factor for electricity is much larger than those for gas and district heating. The standard deviations of the primary EUIs for space heating and electrical appliances were relatively large. The average total primary EUI of the sample units was 163.6 kWh/m^2•year.

4.3.3. CO_2 emission intensities by end use

The statistical values for the CO_2 emission intensities by end use are presented in Table 17, and a box plot of these values is shown in Fig. 5. The average CO_2 emission intensities by end use displayed the following order: electrical appliances > space heating > DHW > lighting > cooking > space cooling > air movement. The values for electrical appliances, space heating, and DHW were large at 191.6, 159.2, and 54.9 10^{-1} kg CO_2/m^2•year, respectively; those for lighting and cooking were 25.4 and 24.3 10^{-1} kgCO_2/m^2•year, respectively; and those for space cooling and air movement were small at 7.3 and 1.7 10^{-1} kgCO_2/m^2•year, respec-

Table 16
Statistics for primary EUIs by end use (kWh/m²•year).

Classification		Space heating	Space cooling	DHW	Lighting	Air movement	Electrical appliances	Cooking	Total
Average (Representative value)		92.1	4.3	28.1	15.3	1.1	119.7	14.1	163.6
Maximum		163.9	9.4	58.2	29.2	2.6	166.7	29.6	229.3
Minimum		33.5	0.9	5.4	7.2	0.1	65.5	4.7	93.3
Percentile	10th	42.7	1.6	11.3	7.5	0.3	76.4	8.3	109.9
	25th	60.5	2.7	15.9	9.7	0.5	93.8	11.0	127.1
	50th	88.3	4.2	26.2	13.6	0.9	123.4	13.1	174.4
	75th	125.1	5.4	36.9	20.4	1.6	150.4	14.9	198.1
	90th	142.4	7.7	48.2	23.0	2.0	161.9	21.4	212.4
Standard deviation		39.6	2.3	15.1	6.4	0.7	33.8	6.3	41.5
Ratio based on average		33.5%	1.6%	10.2%	5.6%	0.4%	43.6%	5.1%	–

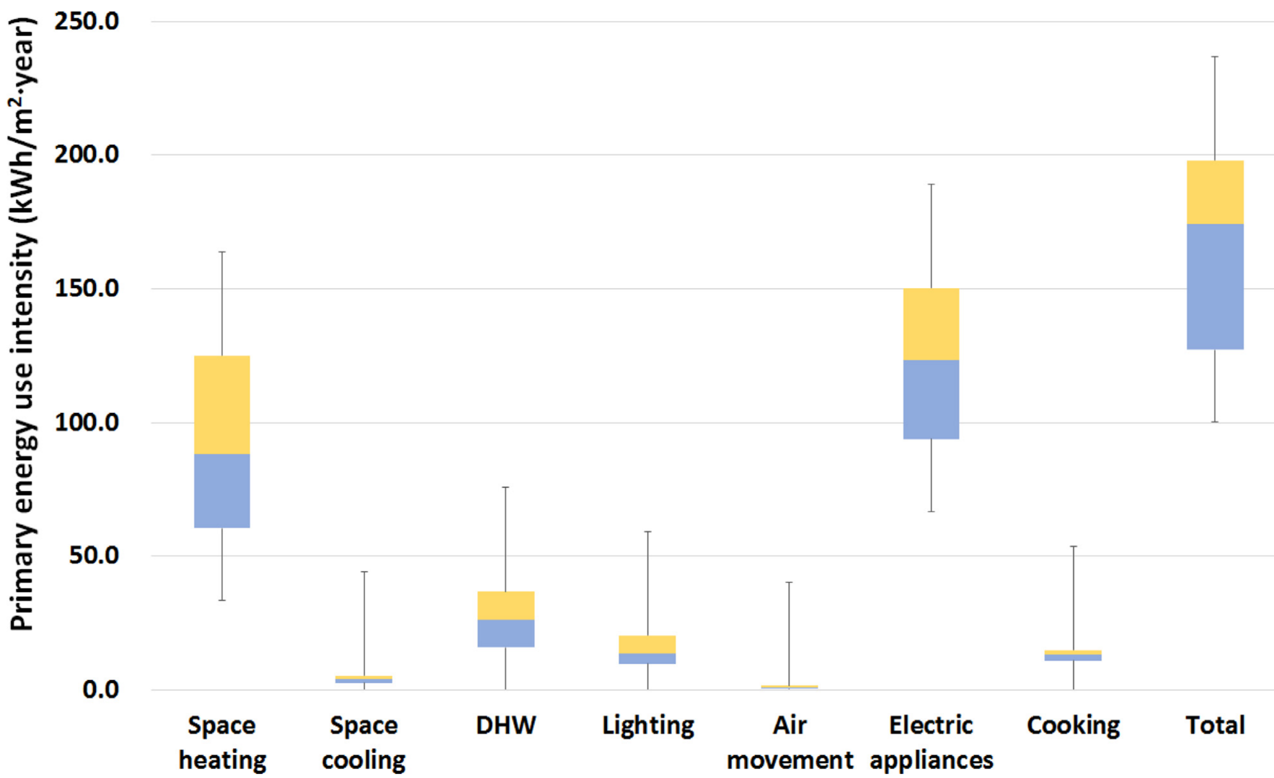


Fig. 4. Box plot of primary EUIs by end use (kWh/m²•year).

Table 17
Statistics for CO_2 emission intensities by end use (10^{-1} $kgCO_2/m^2$•year).

Classification		Space heating	Space cooling	DHW	Lighting	Air movement	Electrical appliances	Cooking	Total
Average (Representative value)		159.2	7.3	54.9	25.4	1.7	191.6	24.3	522.0
Maximum		285.0	16.0	106.2	49.5	4.5	282.7	45.6	771.7
Minimum		61.0	1.6	10.2	12.5	0.1	111.0	8.5	316.0
Percentile	10th	76.0	2.5	27.8	14.8	0.4	123.5	13.0	347.0
	25th	113.3	4.2	32.4	16.8	0.7	156.0	20.0	449.2
	50th	160.7	6.8	50.5	22.2	1.5	178.8	23.6	539.5
	75th	214.9	9.2	78.2	32.1	2.6	218.2	26.6	582.5
	90th	254.2	13.5	89.0	35.2	3.4	270.2	36.0	670.8
Standard deviation		67.7	4.2	27.5	10.3	1.2	55.9	9.6	133.4
Ratio based on average		34.3%	1.6%	11.8%	5.5%	0.4%	41.3%	5.2%	–

tively. The order for the average CO_2 emission intensities by end use was the same as that for the average primary EUIs by end use. Regarding the percentages of the average CO_2 emission intensities by end use, those for electrical appliances, space heating, and DHW were 41.3, 34.3, and 11.8%, respectively, and those for lighting and cooking were 5.5 and 5.2%, respectively. The standard deviations of the CO_2 emission intensities for space heating and electrical appliances were relatively large. The average total CO_2 emission intensity of the sample units was 522.0 10^{-1} $kgCO_2/m^2$•year. The above results indicate that space heating is the most important factor in terms of site energy consumption and electrical appliances are the most important factor in terms of primary energy consumption and CO_2 emissions.

4.4. Analysis of monthly average site EUI distributions by end use

The monthly average site EUIs by end use are presented in Table 18, and graphs of each value and ratio are shown in Fig. 6.

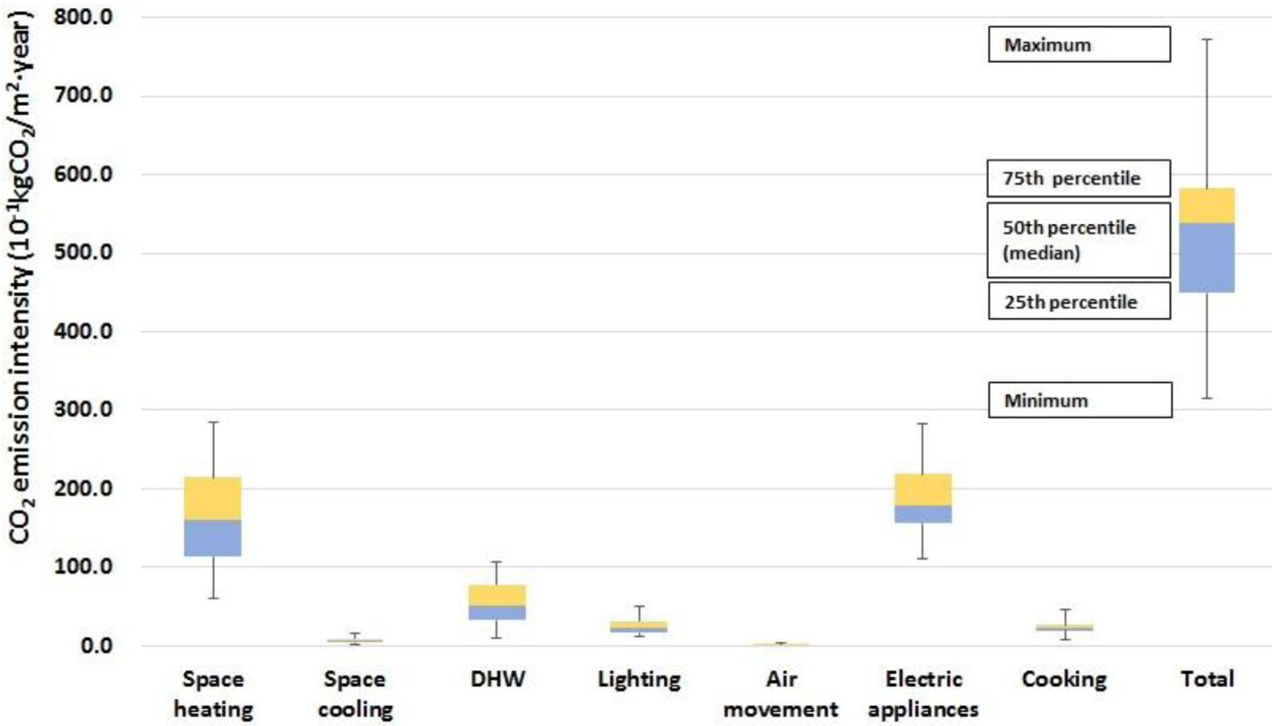


Fig. 5. Box plot of CO_2 emission intensities by end use (10^{-1} kg CO_2/m^2•year).

Table 18
Monthly average site EUIs by end use (kWh/m^2•month).

Month	Space heating	Space cooling	DHW	Lighting	Air movement	Electrical appliances	Cooking	Total
2017.05	1.2	0.0	2.0	0.4	0.033	3.3	0.9	6.7
2017.06	0.0	0.1	1.2	0.4	0.032	3.3	0.9	6.0
2017.07	0.0	0.7	0.9	0.4	0.033	4.1	0.9	6.9
2017.08	0.0	0.5	0.8	0.4	0.033	3.9	0.9	6.4
2017.09	0.8	0.0	1.1	0.4	0.032	3.2	0.9	5.9
2017.10	2.5	0.0	1.4	0.5	0.033	3.3	0.9	8.0
2017.11	9.3	0.0	2.1	0.5	0.031	3.2	1.0	13.8
2017.12	17.0	0.0	3.2	0.5	0.033	3.5	1.0	20.2
2018.01	19.7	0.0	3.4	0.5	0.033	3.6	0.9	22.0
2018.02	16.4	0.0	3.5	0.5	0.030	3.3	0.9	19.0
2018.03	9.5	0.0	3.0	0.5	0.033	3.5	1.0	13.4
2018.04	5.0	0.0	2.2	0.5	0.034	3.2	0.9	9.8

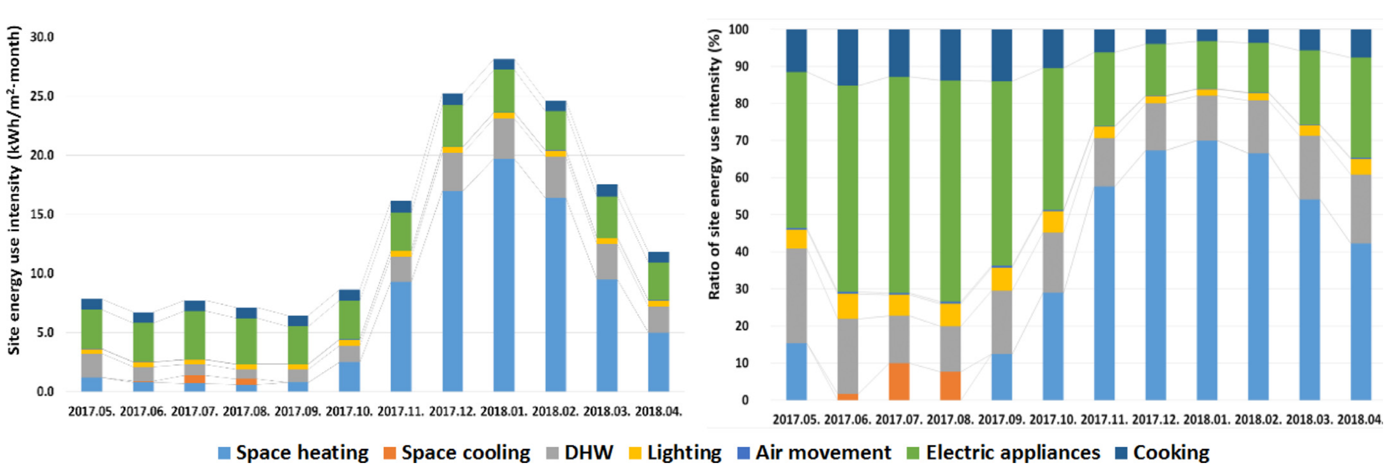


Fig. 6. Distribution of monthly average site EUI values and ratios by end use.

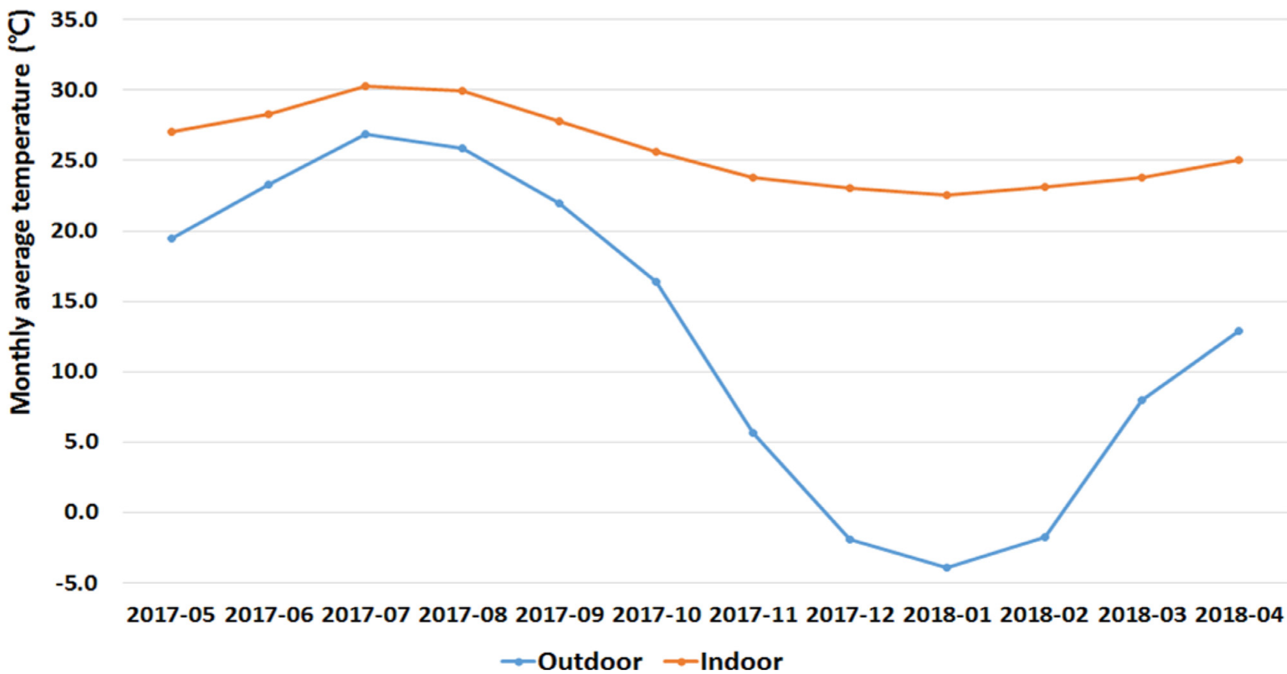


Fig. 7. Monthly average outdoor and indoor temperatures (°C).

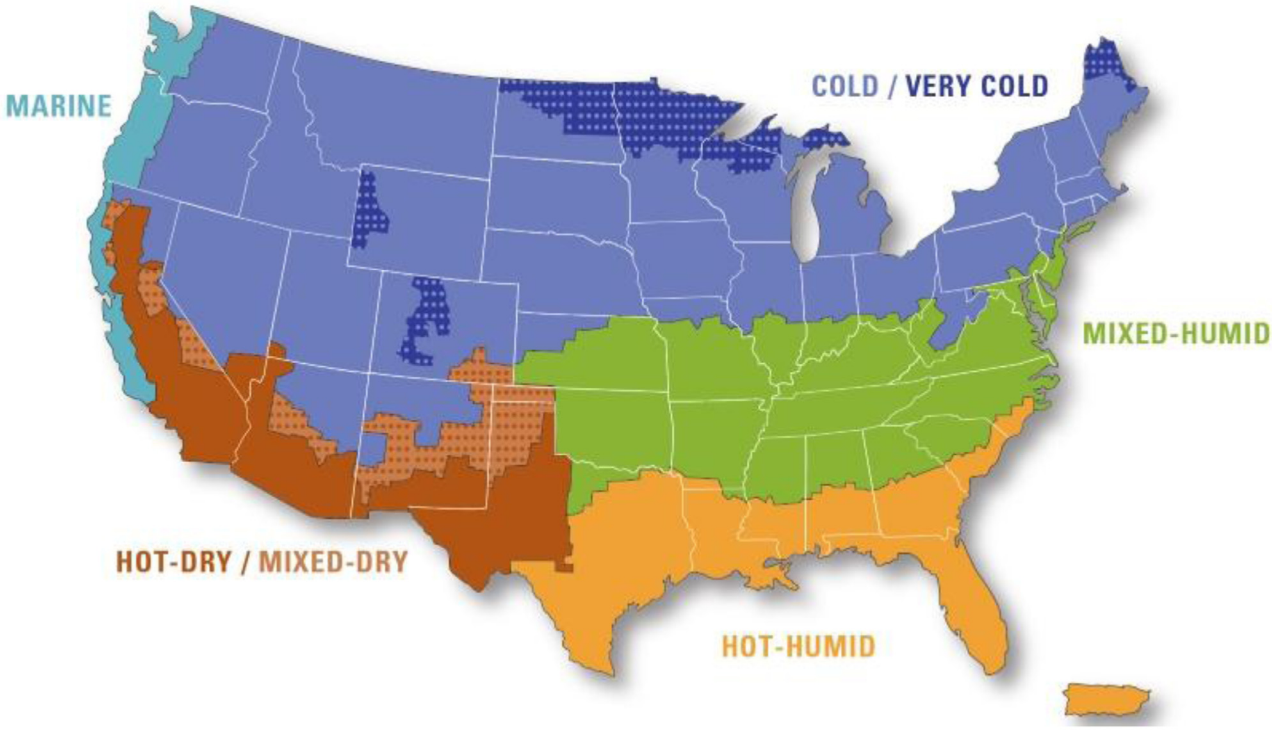
Fig. 7 shows the monthly average outdoor temperatures [29] and the sample unit indoor temperatures. Most indoor temperatures were measured in the living room, with some measured in the bedroom. For aesthetics and the convenience of occupants, the measurement instruments were attached to the wall at a height of 1 m above the floor. In many cases, these instruments were unavoidably placed adjacent to internal heat sources such as televisions, computers, etc. Thus, the measurements in some cases were somewhat higher than the indoor air temperatures at obstruction-free points with good air flow.

The monthly average site EUIs for space heating were large from December–February. The largest value was 19.7 kWh/m^2•month in January, which has the lowest outdoor temperature. From December to February, the average outdoor and indoor temperatures were −2.5 °C and 22.9 °C, respectively. The monthly average site EUIs for space cooling were large in July and August. The largest EUI was 0.7 kWh/m^2•month and obtained in July, the month with the highest outdoor temperature; however, this value was very small compared to the monthly average site EUI for space heating in January. The average indoor temperature in July and August was 30.1 °C, which is quite high considering the thermal comfort range. The average outdoor temperature for the same period was 3.7 °C lower at 26.4 °C. These results are likely attributable to the fact that electric fans are often used as cooling devices in residential buildings in South Korea and that air conditioners are not used often because of the progressive electricity billing system, which charges higher rates for higher electricity use. The monthly average site EUIs for DHW were relatively large in December through March and relatively small in June through October. The monthly average site EUIs for lighting, air movement, and cooking, which are minimally affected by seasonal changes, were relatively steady throughout the year. The monthly average site EUIs for electrical appliances increased slightly in July, August, December, and January because of the use of fans in summer and auxiliary heaters in winter; however, the monthly difference was not large.

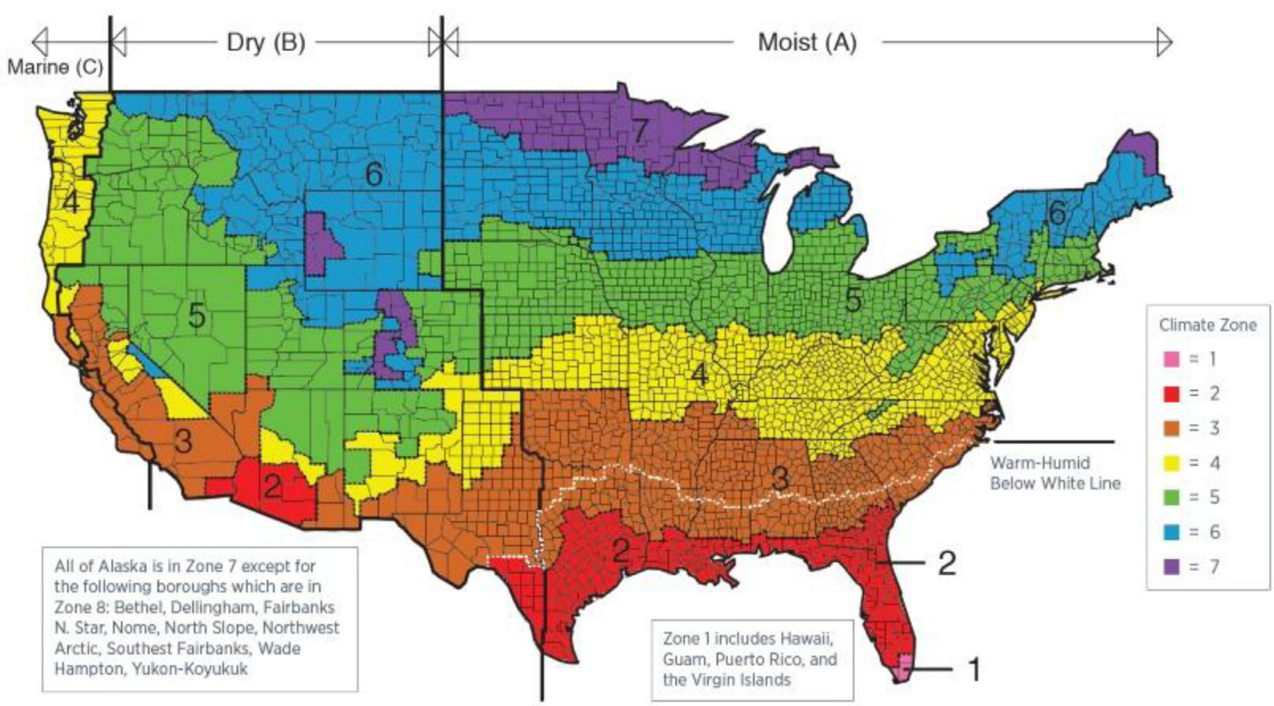
5. Comparison of the average site EUIs by end use from this study with the RECS 2015 data

The magnitudes and trends of the average site EUIs by end use presented in Table 15 were compared and analyzed. As mentioned in the introduction, it is difficult to compare and analyze site EUIs by end use because the building energy information available in South Korea is mainly based on the fuel type and energy consumption information by end use is insufficient. Accordingly, the average site EUIs by end use in this study were compared with the RECS 2015 data (the most recent RECS data) for households located in a mixed-humid climate zone with similar climate conditions to Seoul. In the RECS 2015 data, climate zones are classified according to the Building America program, sponsored by the US Department of Energy's Office of Energy Efficiency and Renewable Energy [30]. The Building America mixed-humid climate zone includes the portions of International Energy Conservation Code (IECC) climate zones 4A and 3A above the warm-humid line as shown in Fig. 8 [31]. Seoul, where the sample units of this study were located, belongs to the IECC climate zone 4A. Thermal criteria for the IECC climate zone 4A are heating degree days (HDD) $\leq$ 3000 and cooling degree days (CDD) $\leq$ 2500. Thermal criteria for the IECC climate zone 3A are HDD $\leq$ 3000 and 2500 $<$ CDD $\leq$ 3500. Base temperatures for obtaining HDD and CDD are 18°C and 10°C, respectively [32]. The RECS 2015 mixed-humid climate zone includes not only the IECC climate zone 4A to which Seoul belongs, but also the IECC climate zone 3A. Hence, the RECS 2015 mixed-humid climate zone has the same HDD level as Seoul and higher CDD level than Seoul. For reference, HDD and CDD of Seoul from May 2017 to April 2018 are 2766 and 2427, respectively [29].

The compared RECS 2015 data included data for not only apartments but also several types of housing units, such as single-family detached, single-family attached, and mobile homes. Tables 19 and 20 present data on the average site energy consumption per household [30] and the average floor area per housing unit [33] for the mixed-humid climate zone in the RECS 2015 data (MBtu and



(a) RECS 2015 (Building America program)



(b) IECC

Fig. 8. Classification of climate zones
(a) RECS 2015 (Building America program)
(b) IECC.

Table 19
Average site energy consumption per household in the mixed-humid climate zone of RECS 2015 (kWh).

Space heating	Space cooling (air conditioning in RECS 2015)	DHW (water heating in RECS 2015)	Refrigerators	Other [a]	Total
10,462.6	2022.2	4425.4	762.0	6242.4	23,650.8

[a] Lighting, appliances (freezers, cooking equipment, laundry machines, dishwashers, minor food-preparation machines, etc.), and electronics (televisions and related devices, computers and related devices, etc.).

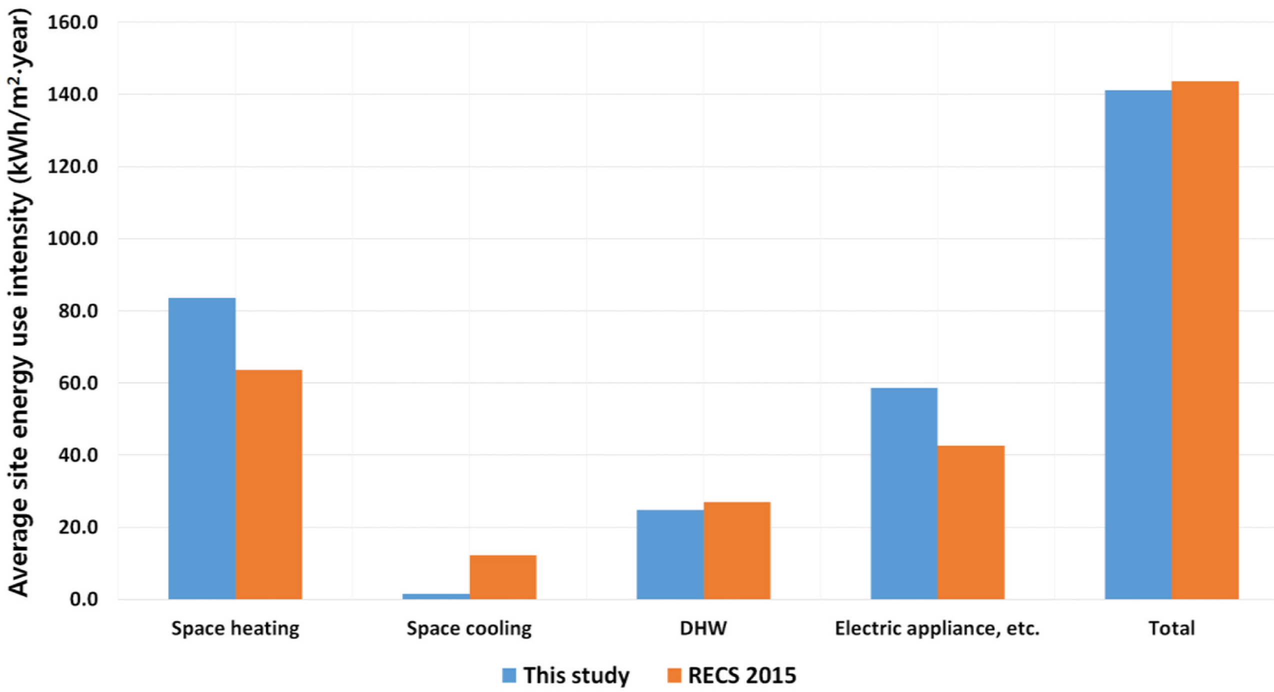


Fig. 9. Comparison of average site EUIs by end use obtained in this study and from RECS 2015.

Table 20
Average floor area per housing unit in the mixed-humid climate zone of RECS 2015 (m^2).

Total	Heated	Cooled
192.6	164.5	142.1

ft^2 are converted to kWh and m^2, respectively). The exclusive use floor area of each sample unit used to determine the EUIs in this study corresponded to the heated floor area. Therefore, the values in Table 19 were divided by the heated floor area values in Table 20 to determine the average site EUIs for the RECS 2015 data.

The classifications by end use employed in this study and RECS 2015 are different. As presented in Table 19, refrigerators were considered as a category in RECS 2015, whereas they were incorporated into the electrical appliance category in this study. Furthermore, the other category (lighting, appliances, and electronics) in RECS 2015 corresponds to lighting, air movement, electrical appliances, and cooking in this study. Therefore, an end use named “electrical appliances, etc.” was added, and the sum of the EUIs for lighting, air movement, electrical appliances, and cooking obtained in this study and the sum of the EUIs for refrigerators and other in the RECS 2015 data were applied. Then, the average site EUIs by end use from this study and RECS 2015 were compared; the results are presented in Table 21 and Fig. 9. The results indicate that the average site EUIs for DHW and the total for all categories are very similar in both cases, but those for the other end uses are somewhat different. The largest difference rate between the results of this study and RECS 2015 was obtained for space cooling. The site EUIs for space heating and electrical appliances, etc. obtained in this study were larger than those determined from the RECS 2015 data; however, the space cooling, DHW, and total site EUIs were larger in the RECS 2015 data. The average site EUIs by end use exhibited the same order in both this study and RECS 2105: space heating > electrical appliances, etc. > DHW > space cooling.

The compared RECS 2015 data are for households located in a mixed-humid climate zone with HDD level equal to Seoul and CDD level higher than Seoul. The differences in EUIs for space heating, space cooling, and electrical appliances, etc. are thought to be due to differences in operating hours and frequently used electrical appliances in accordance with the lifestyles of South Korean apartment unit occupants (in South Korea, rice cookers and auxiliary

Table 21
Comparison of the average site EUIs by end use obtained in this study and from RECS 2015 (kWh/m^2•year).

Classification	Space heating	Space cooling	DHW	Electrical appliances, etc.	Total
This study	83.5	1.5	24.8	58.7	141.2
RECS 2015	63.6	12.3	26.9	42.6	143.7
Variation rate compared to RECS 2015	31.3%	−87.8%	−7.8%	37.8%	−1.7%

heaters belonging to electrical appliances, etc. category are often used and consume considerable amounts of electricity), as well as differences in the evaluation years. In particular, the EUI difference for space cooling is thought to be caused by the fact that Seoul has lower CDD level than the compared region, and the space cooling period using air conditioners and the daily average space cooling hours are relatively short in most sample units of this study, as shown in Table 12. In the RECS, energy characteristics, usage patterns, family members and other information for individual households are collected through surveys and interviews, and this information is combined with energy consumption data for each household provided by energy suppliers. Therefore, the differences in collecting and processing the energy consumption data by end use should be considered.

6. Conclusions

In this paper, statistical data for site and primary EUIs and CO_2 emission intensities by end use were presented based on measurements obtained at 71 sample apartment units located in Seoul from May 2017–April 2018. Furthermore, these data were compared to the RECS 2015 data. The results can be summarized as follows.

(1) The average site EUIs by end use exhibited the following order: space heating > electrical appliances > DHW > cooking > lighting > space cooling > air movement. The values for space heating, electrical appliances, and DHW were large at 83.5, 41.5, and 24.8 kWh/m^2•year, respectively. The value for space heating was overwhelmingly large, and that for electrical appliances was approximately half that for space heating. The DHW value was slightly more than half that for electrical appliances. The average total site EUI of the sample units was 141.2 kWh/m^2•year.

(2) The average primary EUIs by end use displayed the following order: electrical appliances > space heating > DHW > lighting > cooking > space cooling > air movement. The values for electrical appliances, space heating, and DHW were large at 119.7, 92.1, and 28.1 kWh/m^2•year, respectively. The average total primary EUI of the sample units was 163.6 kWh/m^2•year.

(3) The average CO_2 emission intensities by end use exhibited the following order: electrical appliances > space heating > DHW > lighting > cooking > space cooling > air movement. The electrical appliances, space heating, and DHW values were large at 191.6, 159.2, and 54.9 10^{-1} kgCO_2/m^2•year, respectively. The average total CO_2 emission intensity of the sample units was 522.0 10^{-1} kgCO_2/m^2•year. The above results indicate that space heating accounted for the most site energy consumption and electrical appliances accounted for the most primary energy consumption and CO_2 emissions.

(4) The monthly average site EUIs for space heating were large from December to February, and the largest EUI was obtained in January at 19.7 kWh/m^2•month. The monthly average site EUIs for space cooling were large in July and August, and the largest EUI was obtained in July at 0.7 kWh/m^2•month. However, this value was very small compared to the monthly average site EUI for space heating in January. The monthly average site EUIs for DHW were relatively large from December to March and relatively small from June to October. The monthly average site EUIs for lighting, air movement, and cooking, which are minimally affected by seasonal changes, were relatively steady throughout the year. The monthly average site EUIs for electrical appliances increased slightly in July, August, December, and January because of the use of fans in summer and auxiliary heaters in winter; however, the monthly difference was not large.

(5) The average site EUIs by end use obtained in this study were compared to the average site EUIs by end use from RECS 2015 for the climate zone with similar climate conditions to Seoul; the DHW and total values were very similar, but those for the other end uses were somewhat different. In both this study and RECS 2015, the average site EUIs by end use exhibited the same order: space heating > electrical appliances, etc. > DHW > space cooling.

(6) The number of sample apartment units in which energy consumption by end use is being measured will increase gradually until the end of 2019 (to a total of 200 samples). The measured data will be collected continuously. Furthermore, continuous updates will be made to the energy use and CO_2 emission intensity data by end use, as classified by completion year, heat source type, and unit floor area.

Declaration of Competing Interest

None

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