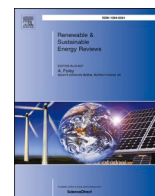




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Changes in energy consumption according to building use type under COVID-19 pandemic in South Korea

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ABSTRACT

An unprecedented global lockdown has been implemented for controlling the spread of COVID-19 in many countries. These actions are reducing the number of coronics, but with the prolonged COVID-19 outbreak, the restrictions on the activities of people are having a significant impact on all industries. Accordingly, this study aimed to statistically analyze changes in building energy consumption under the COVID-19 pandemic in South Korea, as well as identify the relationship between COVID-19 and building energy consumption according to the building use type. As a result, the average rate of changes in electricity and gas energy consumption decreased -4.46% and -10.35% , respectively, compared to the previous year. The energy consumption in most facilities has tended to decrease while energy consumption in residential facilities increased during COVID-19. The rate of change in building energy consumption had a significantly positive correlation with COVID-19 related factors in various facilities (e.g., neighborhood, religious, educational, and research facilities). Significant findings of this study that social distancing by the COVID-19 outbreak, has changed energy consumption according to building use type indicates the need for new energy systems to effectively manage the energy demand at the community level in the Post COVID-19 era.

1. Introduction

The world is still facing a crisis with a heightened alert after the first confirmed case of the novel coronavirus in December 2019. As a result of the rapid spread of the virus, the World Health Organization (WHO) named it coronavirus disease 2019 (COVID-19) and officially declared a global pandemic [1,2]. With the prolonged COVID-19 outbreak, the cumulative number of coronics in September 2020 surpassed 29 million people [3,4]. In order to control the spread of COVID-19, many countries have promulgated an unprecedented global lockdown, and government guidelines (e.g., restrictions on contact and working from home) have been provided [5–8]. Although these actions are reducing the number of coronics, the restrictions on the activities of people are having a significant impact on all industries, along with a serious economic downturn [9,10]. According to the International Energy Agency (IEA), the following changes in the energy sector have been observed, as social activities accompanying energy consumption have significantly reduced

[11–14]: (i) oil demand is sharply reduced due to economic activity and movement control (global oil demand in the first quarter of 2020 decreased by 50% compared to 2019) [14,15]; and (ii) global energy demand is reduced (global energy demand in 2020 decreased by 6% compared to 2019) [14,15].

In line with these global trends, a number of studies have been conducted focusing on environmental and energy changes based on COVID-19. Most studies have analyzed the environmental impact, including the air quality, during the COVID-19 outbreak [16–21]. Previous studies related to temperature and climate changes, as well as environmental policy, were conducted [22–26]. Meanwhile, a few studies on COVID-19 and energy changes were also conducted. Elavarasan et al. [13] and Akrofi et al. [27] investigated the changes in power load caused by COVID-19, and the problems associated with it were analyzed. Kuzemko et al. [28] analyzed the impact of the renewable energy system on energy transitions during the COVID-19 outbreak, and Chen et al. [29] investigated the adoption of the home energy

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management system during the COVID-19 period, taking into account climate change, social and psychological factors, and energy consumption. As a result of a literature review, the guidelines on social distancing following the COVID-19 outbreak have been shown to cause side effects on economic growth, along with a decrease in activities. In contrast, the changes in energy consumption according to building use type can have a positive effect on the environment. However, despite this importance, few studies have been conducted to analyze the change of energy consumption pattern according to building use type. South Korea, particularly, has a high population density, so the number of coronics has been increasing. This will have a significant difference in building energy consumption before and after COVID-19, as lockdown is implemented for an extended period of time.

Therefore, this study aimed to analyze the changes in building energy consumption under the COVID-19 pandemic in South Korea by using the empirical big data from 2019 to 2020. Since South Korea applies different levels of social distancing restrictions for each sector according to regional conditions (i.e., certain cities with a large number of coronics), this study statistically analyzed the relationship between COVID-19 and building energy consumption according to building use type.

2. COVID-19 in South Korea

2.1. COVID-19 outbreak

COVID-19 has spread early in South Korea, which is adjacent to China, and there was a surge in the number of coronics due to the super spreaders. After the first coronics occurred in South Korea in late January, the government sought to control the spread of the virus through quarantine measures. In mid-February, however, religious facilities in Daegu and Gyeongbuk with a high occupancy density produced super spreaders (around 4400 people infected through nth transmission), thus resulting in the national transmission of coronavirus [30]. Furthermore, cluster infections in telecommunications and medical facilities broke out in Daegu in March, and the coronics exceeded 200 within one week [31,32]. Meanwhile, major coronics broke out in telecommunications, entertainment, social gathering, and religious facilities in Seoul and Gyeonggi by the end of May [33–35]. As such, coronics in South Korea were centered in Daegu and Gyeongbuk due to the cluster infections by the super spreaders (about 75% of the coronics in South Korea), as well as in the other regions centered around Seoul

and Gyeonggi that had a higher population density (refer to Table S1 of supplementary data).

2.2. Action to cope with COVID-19

South Korea has more than 20,000 coronics by September 2020, and many people have suffered massive damage, both socially and economically [36]. As the infection is spreading, Korea Centers for Disease Control and Prevention has announced a social distancing policy depending on the number of coronics in order to cope with COVID-19 and control virus dissemination (refer to Fig. 1 and Table 1) [37].

Since January 2020, after the first confirmed case of COVID-19 from Wuhan, China, the South Korean government proposed a guideline for the public, such as personal hygiene management and avoiding crowded places. Citizens were required to self-isolate, wear masks, and stay at home according to the social distancing guidelines provided by the South Korean government. From late February to early March 2020, the citizens in Daegu and Gyeongbuk started the voluntary ‘self-social distancing’ amid the cluster infections in the region, and the Daegu local government limited the social contact and economic activities from February to March, which corresponds to the guideline in Social Distancing Level 2 [38,39]. In order to prevent the spread of the infection, Seoul exercised an early form of Social Distancing Level 1 [40]. Social Distancing Level 1 allows general activities to be carried out in accordance with preventive measures against the pandemic. However, some companies have started work-from-home schemes, thereby leading to the decrease in people’s economic activities.

As coronavirus gradually spread from Daegu and Gyeongbuk to the whole country, the South Korean government raised the crisis level from ‘Alert’ to ‘Serious’ (the highest level) in mid-March 2020, and enacted the nationwide Social Distancing Level 2 [31]. In comparison to Social Distancing Level 1, Social Distancing Level 2 brings in much stricter measures, and companies limited the number of staff at work. Work-from-home order became mandatory, and schools postponed the start of the term or offered online, remote lectures. Moreover, the operation of multi-purpose facilities (e.g., library, museum, national park, etc.) was forcibly closed, and the operation of facilities susceptible to cluster infection (e.g., entertainment pub, karaoke, religious facilities, performance hall, etc.) was stopped. Since the government suggested delaying or canceling gatherings and staying at home, people were restricted from carrying out economic activities and they were unable to use commercial facilities. Due to online learning and working from

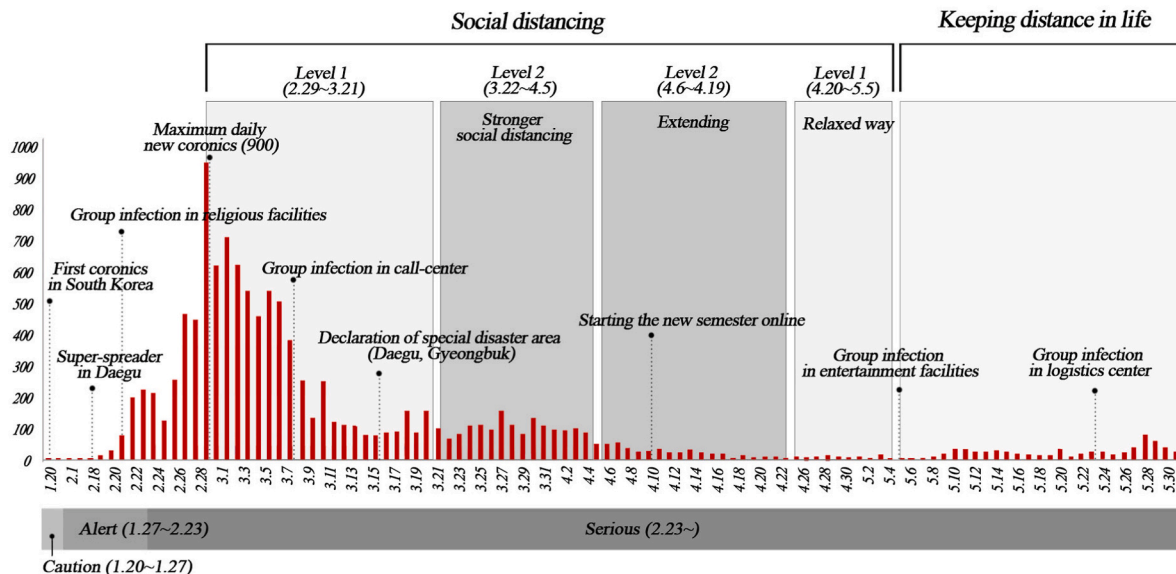


Fig. 1. Outbreak trend of COVID-19 and government action in South Korea.

Table 1
Government action to cope with COVID-19 in South Korea.

Classification	Social Distancing Level 1	Social Distancing Level 2	Social Distancing Level 3
Period	2020.02.29–2020.03.21 2020.04.20–2020.05.05	2020.03.22–2020.04.19	–
Daily coronics (confirmed cases)	Less than 50 people	50 to 100 people	Over 100 people, doubling ^a
Definition	Compliance with quarantine rules and daily activities	Stay-at-home order	Prohibition of all activities other than essential economic activities
Face-to-face gathering	Compliance with quarantine rules and daily activities	Ban gatherings of 50 or more people indoors and 100 or more people outdoors	Ban gatherings of 10 people
Sports facilities	Limited number of spectators	No spectators	Suspension of the game and closing of the stadium
Public facilities	Partial suspension	Suspension	Suspension
Multi-purpose facilities (private)	Operational restriction on high-risk facilities	Prohibition of operation of high-risk facilities, and restrictions on personnel per 4 m ² for other facilities	Closed after 21:00
Educational facilities	Go to school (2/3), online learning	Go to school (1/3), online learning	Closing of school, online learning
Public purpose facility and public enterprise	Minimization of working density	Minimization of working density	Work-from-home scheme for all employees, excluding the required personnel
Private-purpose facility and private company	Promotion of working from home	Recommendation of limiting the number of workers	Recommendation to work from home, excluding the required personnel

Note: As the Level goes from 1 to 3, the number of coronics increases, and social distancing is reinforced.

^a Doubling is an indicator of the rate of spread. It is the case where there is more than twice the number of coronics compared to the previous day or the case of group infection more than twice a week.

home, the time spent living at home has increased. As the number of newly coronics decreased to 64% in Daegu, Gyeongbuk, and the rest of the country, and social distancing measures in Daegu and Gyeongbuk were lowered to Level 1 [38,41].

In April 2020, despite the rapid response effort made against cluster infections, the number of new infections in the country continued to increase, along with the global transmission of COVID-19 and the soaring death toll. Accordingly, the South Korean government extended its Social Distancing Level 2 to April 19, 2020 [41]. Later in May 2020, due to the cluster infections in Seoul and Gyeonggi, the country implemented both social distancing Levels 1 and 2 depending on the number of coronics [42]. As a result, social distancing, industrial operations, and traffic were significantly reduced than normal, and the energy consumption changed [43].

3. Materials and methods

3.1. Data processing

Big data is used in the analysis of the relationship between COVID-19 and building energy consumption by building use type in this study, which includes all building electricity-gas energy data and regional COVID-19 data in South Korea. The collected raw data cannot be used directly for the analysis since various data corrections (e.g., error data, missing values, and unit differences) are required [44,45]. Accordingly, this study aimed to improve the quality of data analysis results by arranging and processing the collected big data in a form that can be analyzed. In this study, data processing was conducted according to the following four steps: (i) data collection; (ii) data filtering; (iii) data unification; and (iv) climate adjustment.

3.1.1. Data collection

The analysis period of this study was set from January 2020, when the first COVID-19 case was reported in South Korea, to May 2020, when the current data could be collected. In order to analyze the changes in building energy consumption by building use type under COVID-19 in South Korea, this study collected the following variables. First, the monthly building energy consumption according to building use type should be collected in order to analyze the differences due to the COVID-19 pandemic and actions from the government such as social distancing level [46–49]. The data on building use type and building energy consumption (i.e., electricity and gas energy) were collected from the *Korea*

Appraisal Board (KAB) of South Korea [50]. Since the heating and cooling energy loads in the building energy consumption differ by regional climate, the regional climate data need to be collected in order to compare the building energy consumption in 2020 to 2019 under identical conditions [51,52]. Additionally, the data on building energy consumption and building use type was collected from January to May for six years from 2015 to 2020. It was used in data processing for the filtering of this study. As a result, a total of 6,553,449 building data was collected. Meanwhile, the climate data (i.e., monthly air temperature) was collected from the *Korea Meteorological Administration (KMA)* [53].

Secondly, the study should collect time-variant COVID-19 related variables (i.e., number of coronics, cumulative number of coronics, cumulative number of death cases, incidence rate death cases, and morbidity rate). As the social distancing level changes by the number of coronics and infections [54], the restriction in the use of multi-purpose facilities may affect building energy consumption (refer to Table 2). For the COVID-19 related data, the study collected weekly regional data published by the *Korea Disease Control and Prevention Agency (KDCA)* [36].

3.1.2. Data filtering

In order to improve the database quality and ensure the reliability of the analysis results, data filtering was performed as follows. First, the data on the buildings that have been newly constructed and expanded on the site, and where the building use type has been changed for six years (analysis period from 2015 to 2020) were excluded. Second, among a total of 28 building use types defined following South Korea laws, the data on the buildings with the 10 building use types that can be directly affected by social distancing actions under COVID-19 were used (refer to Table S2 of supplementary data). Third, among the three main energies (electricity, gas energy, and district heating) consumed by buildings in South Korea, the data on the buildings that consume electricity and gas energy were used. The distribution rate of district heating in South Korea was only 10% in 2015 [55], and district heating was mainly used only in residential buildings, resulting in biased analysis results, so data on buildings using district heating were excluded. Fourth, the data on the buildings with zero energy were excluded in order to analyze the energy consumption of a normally operating building. Fifth, the data on the buildings with missing and without matching electricity or gas energy consumption data were excluded from the database. Finally, 0.5% of each of the upper and lower outliers (i.e., 1% of the total) were removed from the collected database, since very small or large values that are out

Table 2
Variables for analysis the change in building energy consumption under COVID-19.

Classification		Description	Sources		
Building characteristics	Building use type	Multi-family residences	[50]		
		Single-family residences			
		Medical facilities			
		Offices			
		Neighborhood facilities-A			
		Neighborhood facilities-B			
		Sales			
		Hotels			
		Religious facilities			
		Education and research facilities			
		Electricity		()kWh	[50]
		Gas energy		()MJ	
		Building energy consumption		Monthly air temperature	(°C)
COVID-19 related data	No. of coronics		[54]		
	Cumulative No. of coronics	N			
	Cumulative No. of death cases	N			
	Incidence rate of death cases	()%			
	Morbidity rate	()%			

of the range of the observed data may negatively affect the analysis results [56]. As a result, this study established a database consisting of 1, 175,744 buildings through data filtering steps (refer to Table S3 of supplementary data).

3.1.3. Data unification

When comparing the building energy consumption data composed of different energy types (i.e., electricity and gas energy), absolute metrics (i.e., raw data on the electricity and gas energy data) should be converted into comparable value (i.e., primary energy consumption). In order to convert primary energy consumption (i.e., tonne of oil equivalent [toe]), national conversion factors for electricity (2.75) and gas energy (1.1) were used in this study in order to convert energy unit [57]. After converting the energy consumption into the primary energy consumption in toe units, it was converted in kWh unit data to better understand the building energy consumption database. Since 1 toe is 107 kcal and 1 kWh has 860 kcal of heat, by multiplying the primary energy consumption by about 11,628, the data in toe units can be converted into kWh.

3.1.4. Climate adjustment

Building energy consumption, including heating and cooling energy loads, changes considerably by regional climatic and geological characteristics, and the pattern of changes differs by building use type. In particular, the majority of previous papers suggested that weather factors, such as outdoor temperature, have a significant effect on heating and cooling energy consumption [58,59]. That is, yearly outdoor air temperature changes and, accordingly, heating and cooling loads change. It is therefore unreasonable to evaluate and compare heating and cooling loads by year based on the raw data of building energy consumption (comparison of energy consumption in 2019 and 2020). In order to solve this problem, climate adjustment was used to normalize building energy consumption for outdoor air temperature on a periodical time step (weekly, monthly, or annually).

Climate adjustment makes it possible to compare energy consumptions in different periods depending on an identical basis [60]. According to the previous study, climate adjustment was performed using

various energy saving evaluation software including inverse modeling toolkit research project (IMT RP-1050) provided the ASHRAE [61,62]. IMT RP-1050 can calculate the correction factor through Variable-Based Degree Day Method (VBDDM) and Change-Point model (CP) based on independent variables such as the values of HDDs and CDDs. However, the Excel-based calculator was used in this study based on its methodology instead of using IMT RP-1050. Because this toolkit needs to convert the input and output data units to SI units for use in this study due to the using US customary units of IMT RP-1050. Moreover, since this study, which used more than 10 million big-data, it is difficult to convert the data units. This study used Microsoft Excel and SPSS based-Four Parameter Model (4P) consisting of monthly HDDs CDDs instead of IMT RP-1050 for easy calculation and least time-consuming.

Therefore, this study performed climate adjustment based on the excel-based calculator for conducting multi-variate regression between building energy consumption and the data on the heating and cooling degree day (HDD and CDD), which are representative indicators of the local climate. Climate adjustment of this study was carried out in a two-step process: (i) Calculation of HDDs and CDDs from climate data; (ii) Derivation of correction factors through multi-variate regression.

First, through the open-sourced data provided by the KMA, monthly HDDs and CDDs were collected for each building use type in 18 administrative districts from five years (2015–2019). Currently, the data on the energy consumption by building use types is only provided for five years in South Korea. In addition, the balance point temperature was set to 18.3 °C (65 °F) based on the international standard recommended by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) [63,64]. Similarly, KMA and the Society of Air-conditioning and Refrigerating Engineers of Korea (SAREK) use 18.3 °C as the balance point temperature [65]. Secondly, the climate adjustment was performed by using data consisting of electricity and gas energy. The monthly energy consumption by building use type was collected from the National Building Energy Greenhouse Gas Information System established by the KAB [50]. Eq. (1) shows the multi-variate regression between the independent variables (i.e., monthly HDD and CDD), and the dependent variable (the monthly energy consumption). Moreover, b_{0ij} is the non-seasonal energy consumption that does not affect the heating and cooling energy, while b_{1ij} and b_{2ij} are the sensitivity level for HDD and CDD building energy consumption. Eq. (2) shows the process of determining the correction factor (CORR_{ijk}) using the regression coefficient (b_{1ij} and b_{2ij}) acquired from the above multi-variate regression. Finally, using Eq. (3), the correction factor can be deducted from the raw data of the monthly building energy consumption, which was determined above, in order to calculate the normalized building energy consumption after the climate adjustment.

$$Y_{ijk} = b_{0ij} + b_{1ij} \cdot HDD_{ijk} + b_{2ij} \cdot CDD_{ijk} \quad (1)$$

$$CORR_{ijk} = \hat{b}_{1ij} \cdot (HDD_{ijk} - NHDD_{ij}) + \hat{b}_{2ij} \cdot (CDD_{ijk} - NCDD_{ij}) \quad (2)$$

$$Y_{ijk_{ta}} = Y_{ijk} - CORR_{ijk} \quad (3)$$

Where, Y_{ijk} stands for the electricity or gas consumption for district i , building use type j at month k ; b_{0ij} stands for non-seasonal energy consumptions; b_{1ij} stands for a regression coefficient of HDD_{ijk} ; HDD_{ijk} stands for heating degree days for district i , building use type j at month k ; b_{2ij} stands for a regression coefficient of CDD_{ijk} ; CDD_{ijk} stands for cooling degree days for district i , building use type j at month k ; $CORR_{ijk}$ stands for correction factor for district i , building use type j at month k ; $NHDD_{ij}$ stands for the 10-year average of HDD_{ij} for the k th month; $NCDD_{ij}$ stands for the 10 year average of CDD_{ij} for the k th month; and $Y_{ijk_{ta}}$ stands for temperature adjusted electricity or gas energy consumption.

3.2. Statistical analysis

Using the big data on national energy consumption, this study analyzed the changes in building energy consumption under COVID-19 in South Korea. In order to deal with big data, the data processing and statistical analysis were conducted by using R software (version: 4.0.2).

Correlation analysis is one of the techniques that statistically verify the relationship between variables with continuous attributes [66,67]. In order to analyze the effect of COVID-19 on building energy consumption, correlation analysis between the building energy consumption variables and COVID-19 variables was conducted based on the empirical database. In this study, the variables are normally distributed. Therefore, Pearson correlation analysis can be used among the parametric statistical methods.

In this study, Pearson correlation analysis was conducted in the following three process: (i) Definition of target variables; (ii) Log transformation for getting closer to a normal distribution; and (iii) Determination of correlation coefficients. First, target variables to be analyzed for correlation between the two sides were defined (refer to Table 2 in Step 2.1). The target variables related to COVID-19 are defined as “new coronics (n)”, “cumulative number of coronics (n)”, and “incidence rate (n)”, while the target variables related to building energy consumption according to the building use type was defined as “the rate of change”. In this regard, the rate of change (ROC) (%) in building energy consumption by building use type in 2020 compared to 2019 can be calculated by using Eq. (4). As a result, correlation analysis of this study was performed for a total of 60 times (1EA × 3EA × 10EA × 2 EA) for 10 building use types and two energy sources (electricity and gas energy).

Second, in order to prevent the anomalies due to the difference in data values (e.g., there is a huge difference in the number of coronics due to the super spreaders) from degrading the accuracy of the results in the correlation analysis, all variables were converted by log information so that the distribution of all variables is in bell-shaped distribution [68].

Third, Correlation coefficients (r) as the resulting values can range from -1 to $+1$. If $r > 0$, there is a positive correlation between variables. If $r < 0$, there is a negative correlation between variables [69,70]. In general, the higher the absolute value of correlational coefficient (r), the stronger the correlation between two variables. For example, the correlation coefficient between “rate of change (%) in electricity by building use types in 2020 compared to 2019” and “New coronics (n)” of apartment houses is 0.343, and p is 0.002, which is statistically significant. This indicates that two variables have a statistically significant positive correlation.

$$ROC(\%) = \left| \frac{Y_{ijk}^{2020} - Y_{ijk}^{2019}}{Y_{ijk}^{2019}} \right| \times 100 \quad (4)$$

Where, ROC(%) stands for the rate of change in energy consumption in 2020 compared to 2019; Y_{ijk}^{2020} stands for the total energy consumption for district i , building use type j at month k , 2020; and Y_{ijk}^{2019} stands for the total energy consumption for district i , building use type j at month k , 2019.

This study compared the monthly building energy consumption according to building use type in the same month in the current year (2020) versus the previous year (2019). In order to conduct an in-depth analysis of the building energy consumption, the energy sources were divided into electricity and gas energy, and Daegu and Gyeongbuk, which occupied 75% of the total coronics, were separated from the other regions.

4. Results and discussions

4.1. Correlation between energy consumption by building use type and COVID-19

As variables were normally distributed, Pearson correlation analysis was performed in order to identified the significant correlation between COVID-19 and the rate of change in building energy consumption. Table 3 shows the correlation coefficient (r) and significant value (p) between COVID-19 related factors (new coronics[n], the cumulative number of coronics [n], and incidence rate [%]) and each rate of change (%) in electricity and gas energy consumption in 2020 compared to 2019 according to 10 building use types.

As shown in Table 3, the rate of change in electricity had a significantly positive correlation with both new coronics and cumulative number of coronics in the following six building use types: (i) multi-family residences (r : 0.343, 0.519), (ii) neighborhood facilities-A (r : 0.344, 0.501), (iii) neighborhood facilities-B (r : 0.340, 0.488), (iv) hotels (r : 0.359, 0.591), (v) religious facilities (r : 0.415, 648), and (vi) educational and research facilities (r : 0.362, 0.625). Similarly, the rate of change in gas energy consumption had a significantly positive correlation with both new coronics and the cumulative number of coronics in the following four building use types: (i) neighborhood facilities-A (r : 0.280, 0.452), (ii) neighborhood facilities-B (r : 0.354, 0.566), (iii) hotel (r : 0.212, 0.447), and (iv) religious facilities (r : 0.343, 0.590).

The results of the study have shown that the nationwide COVID-19 lockdown, which was implemented as the coronics increased, restricted people’s activities, thus affecting the energy consumption based on various building use types. In particular, as the people spend more time indoors, the electricity energy consumption of multi-family residencies responded to the number of coronics sensitively. Furthermore, it has been shown that as the government and local authorities restricted people’s economic, social, and religious activities, as well as prevented them from accessing related facilities, the electricity and gas energy consumption in neighborhood facilities-A and -B, which included community and utility facilities, religious facilities (e.g., catholic churches and temples), and hotels, among others, had a close relation to the increase of confirmed cases. At the same time, due to the administrative ordinances that reduced the number of students in school through online learning, it was determined that there was a significant correlation between the number of coronics and the electricity and gas energy consumption in educational and research facilities.

4.2. Changes in energy consumption by building use type after COVID-19

4.2.1. Energy consumption by building use type according to social distancing level

Fig. 2 shows the average change rate in monthly building electricity and gas energy consumption according to building use type in the current year (2020) versus the previous year (2019). Detailed results of changes in monthly electricity and gas energy consumption by building use type (before and after the COVID-19 outbreak) are provided below.

In the case of residential facilities (i.e., multi-family and single-family residences), the monthly electricity consumption between March and May, at which time social distancing had been implemented, increased to year. Moreover, the monthly gas energy consumption showed a yearly difference within 3%, except in April when Social Distancing Level 2 was implemented to control the expansion of COVID-19.

In the case of commercial facilities (i.e., neighborhood facilities-A, neighborhood facilities-B, and sales), the monthly electricity and gas energy consumption in January, which is the early period of the COVID-19 outbreak, showed a yearly difference within 1%, but decreased between February and May. In April, when Social Distancing Level 2 was implemented, businesses and people’s economic activities have been restricted, thereby resulting in the largest reduction in the monthly

Table 3
Results of the Pearson correlation coefficient (*r*).

The rate of change (%)	Building use type	New coronics(n)		Cumulative number of coronics (n)		Incidence rate (%)		
		r	p	R	p	r	p	
Electricity by building use types in 2020 compared to 2019	Single-family residences	0.165	0.144	0.176	0.119	0.114	0.312	
	Multi-family residences	0.343**	0.002	0.519**	0.001	0.265*	0.017	
	Medical facilities	0.083	0.478	0.077	0.514	0.040	0.731	
	Offices	0.033	0.773	0.195	0.083	0.055	0.063	
	Neighborhood facilities-A	0.344**	0.002	0.501**	0.001	0.276*	0.013	
	Neighborhood facilities-B	0.340**	0.002	0.488**	0.001	0.301**	0.007	
	Sales	0.014	0.222	0.322**	0.007	0.185	0.126	
	Hotels	0.359**	0.001	0.591**	0.001	0.216	0.054	
	Religious facilities	0.415**	0.001	0.648**	0.001	0.233*	0.037	
	Education and research facilities	0.362**	0.001	0.625**	0.001	0.178	0.114	
	Gas energy by building use types in 2020 compared to 2019	Single-family residence	-0.042	0.656	0.141	0.135	-0.129	0.172
		Multi-family residence	0.004	0.971	0.127	0.262	-0.061	0.592
Medical facilities		-0.105	0.369	0.043	0.713	-0.145	0.216	
Office		-0.065	0.568	0.212	0.058	-0.198	0.079	
Neighborhood facilities-A		0.280*	0.012	0.452**	0.001	0.168	0.136	
Neighborhood facilities-B		0.354**	0.001	0.566**	0.001	0.205	0.068	
Sales		0.222	0.056	0.302**	0.008	0.136	0.244	
Hotel		0.212*	0.023	0.447**	0.001	0.137	0.144	
Religious facilities		0.343**	0.002	0.590**	0.001	0.145	0.201	
Education and research facilities		0.152	0.108	0.380**	0.001	0.110	0.245	

Note: *r* stands for correlation coefficient; *p* stands for statistical significance of correlation coefficient; bold values indicate that the coefficient is significant at the 0.05 level; * stands for significance difference ($p < 0.05$); and ** stands for significance difference ($p < 0.01$).

electricity and gas energy consumption to year. As with the alleviation of Social Distancing Level 1 in May, the amount of reduction to year decreased.

In the case of offices, the monthly electricity consumption, excluding March, showed a yearly difference within 5%, and the monthly gas energy consumption decreased in all months. As opposed to the monthly gas energy consumption, the monthly electricity consumption was similar to that of the previous year despite the implementation of the work-from-home scheme due to the electricity equipment (i.e., computer, communication equipment, refrigerator, copier, etc.) that consumes energy regardless of occupancy [71]. However, the electricity consumption of the offices to year increased by 1.5% in March 2020, at which time Social Distancing Level 1 was first implemented, as the working hours were monitored in public offices that manage the national emergency system for preventive measures against the pandemic. Similar to the other facilities, except residential facilities, the number of work-from-home employees increased in April when Social Distancing Level 2 was implemented, so that the hot water and heating demand decreased, thereby resulting in the largest amount of reduction in the gas energy consumption.

In the case of educational and research facilities, the monthly electricity and gas energy consumption to year increased considerably. Due to the nationwide postponement of the start of the term and online learning after the start of term, the monthly electricity and gas energy consumption in educational facilities showed the smallest decrease among all building use types. The energy consumption in research facilities also continued to decrease in March and April as the implementation of Social Distancing Level 2 led to the increase of work-from-home cases, and started to return to normal in May as social distancing returned to Level 1.

As a result, the monthly energy consumption in January, which is the onset of the COVID-19 outbreak, was similar to that of the previous year. Since then, as the social distancing measures were strengthened, the building energy consumption increased. This indicates that the increase in the number of coronics due to the COVID-19 pandemic moves the social distancing level up and reduces the building energy consumption.

4.2.2. Energy consumption by building use type according to regional infection of COVID-19

Daegu and Gyeongbuk occupied about 75% of the total coronics between January and May 2020, and the increase rate was 28.2 times

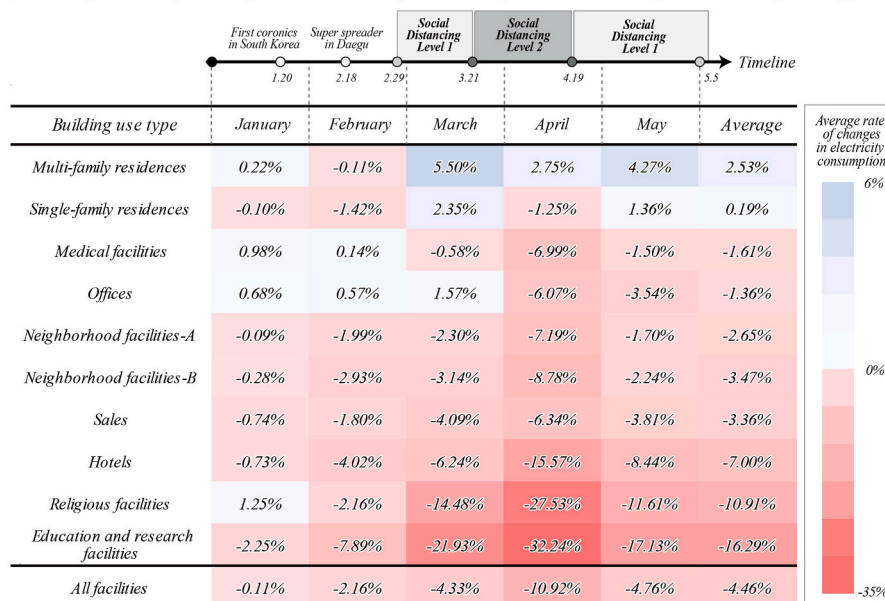
higher than that of the other regions. In order to determine the effect of the COVID-19 pandemic on building energy consumption, this study separated Daegu and Gyeongbuk regions, where the prevalence rate and the transmission rate were higher than the other regions, from the other regions in the analysis.

Fig. 3 shows the average rates of change in electricity and gas energy consumption of 10 building use types in Daegu, Gyeongbuk, and other regions according to the regional infection of COVID-19. In addition, to determine the building energy consumption by region, the maps of Figs. 4 and 5 show the average rate of change of 16 administrative divisions. In Figs. 4 and 5, blue-shaded regions indicate increased energy consumption in 2020 compared to 2019. Red-shaded regions, on the other hand, indicate decreased energy consumption. As an exception, the area was treated as a white blank due to lack of data on the energy consumption of sales and medical facilities in Sejong Special Self-Governing City. Detailed explanations are below.

In the case of multi-family residences, the national electricity consumption to year increased. Daegu and Gyeongbuk showed an increase by about 3.62% and 2.72%, respectively, while other regions increased by 2.44%. Therefore, it shows that electronic appliance usage in daily life increased as people limited their outdoor activities and stayed indoors. On the other hand, the gas energy consumption in Daegu and Gyeongbuk increased by 1.34% and 3.72%, respectively, while that of the other regions decreased by 3%. In recent years, despite the tendency of the gas energy consumption of multi-family residences to decrease, thanks to the strengthening insulation standards [72], the gas energy consumption of Daegu and Gyeongbuk increased, which means that stricter social distancing has been implemented compared to the other regions.

In the case of single-family residences, electricity consumption in Daegu and Gyeongbuk, and in other regions increased by 0.16% and 0.19%, respectively, which are about the same as in the previous year. On the other hand, the gas energy consumption in Daegu and Gyeongbuk increased by 0.29% and 1.94%, respectively, whereas that of the other regions decreased by 3.66%. Single-family residences are houses equipped with facilities for one household to live and they are used temporarily by students or workers. The prolonged COVID-19 outbreak has led to the closure of schools and educational facilities, as well as businesses in residential areas, and there is a considerable increase in empty single-family residences [73]. Therefore, despite being residential facilities, the empty residential facilities due to COVID-19 may have

(A) Average rate of changes in electricity consumption according to building use type



(B) Average rate of changes in gas energy consumption according to building use type

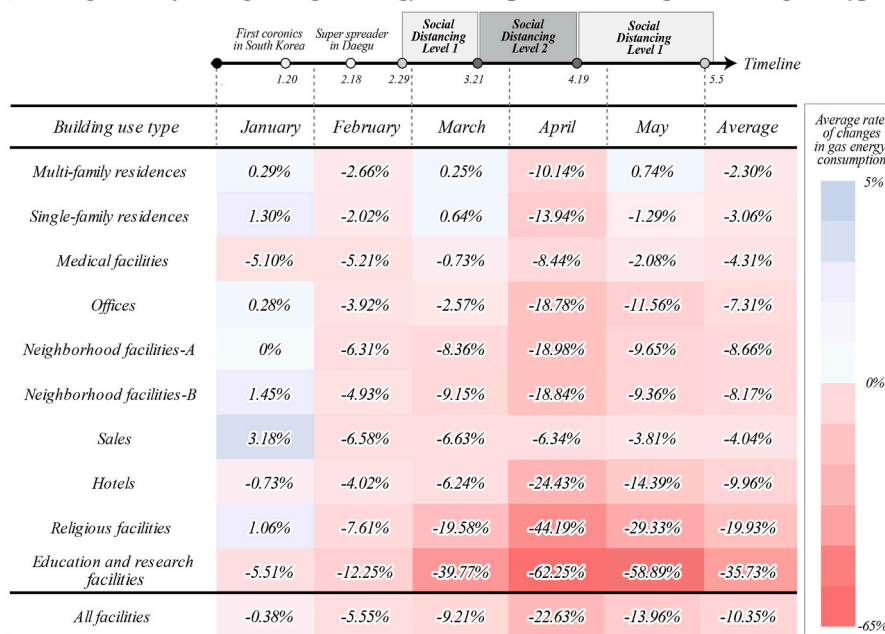


Fig. 2. Changes in monthly electricity consumption by building use type.

affected the reduction of energy consumption in single-family residences compared to multi-family residences.

In the case of medical facilities, electricity consumption in Daegu and Gyeongbuk, and in other regions decreased by 2.7% and 2.1%, respectively. Furthermore, gas energy consumption in Daegu and Gyeongbuk, and in other regions decreased by 3.41% and 4.45%, respectively. Despite the increasing number of coronics due to the COVID-19 outbreak, the energy consumption of medical facilities also decreased. There are a total of 29 hospital in South Korea that own negative pressure isolation rooms, and there are only 535 beds (as of November 2019). Accordingly, the unexpected increase in the transmission has led to the lack of negative pressure isolation rooms, and many coronics were placed under home isolation and treatment rather than hospitalization [74]. Therefore, the increase in coronics may have affected the energy

consumption of medical facilities, but the energy consumption may have been decreased as people’s economic and social activities have become restricted. The ratio of those who visited hospitals decreased and, accordingly, the energy consumption also decreased.

In the case of offices, electricity consumption in Daegu, Gyeongbuk, and other regions decreased by 0.99%, 5.01%, and 1.2%, respectively. Gas energy consumption in Daegu and Gyeongbuk slightly increased by 0.09%; however, gas energy consumption in the other regions decreased by 8.37%. This is because the operation of public facilities, public purpose facilities, and public enterprises has been partially or fully suspended due to social distancing. As work-from-home scheme for private-purpose facilities and private companies was recommended, the ratio of workers who commuted decreased (refer to Table 1 and Fig. 1).

In the case of neighborhood facilities-A, electricity consumption in

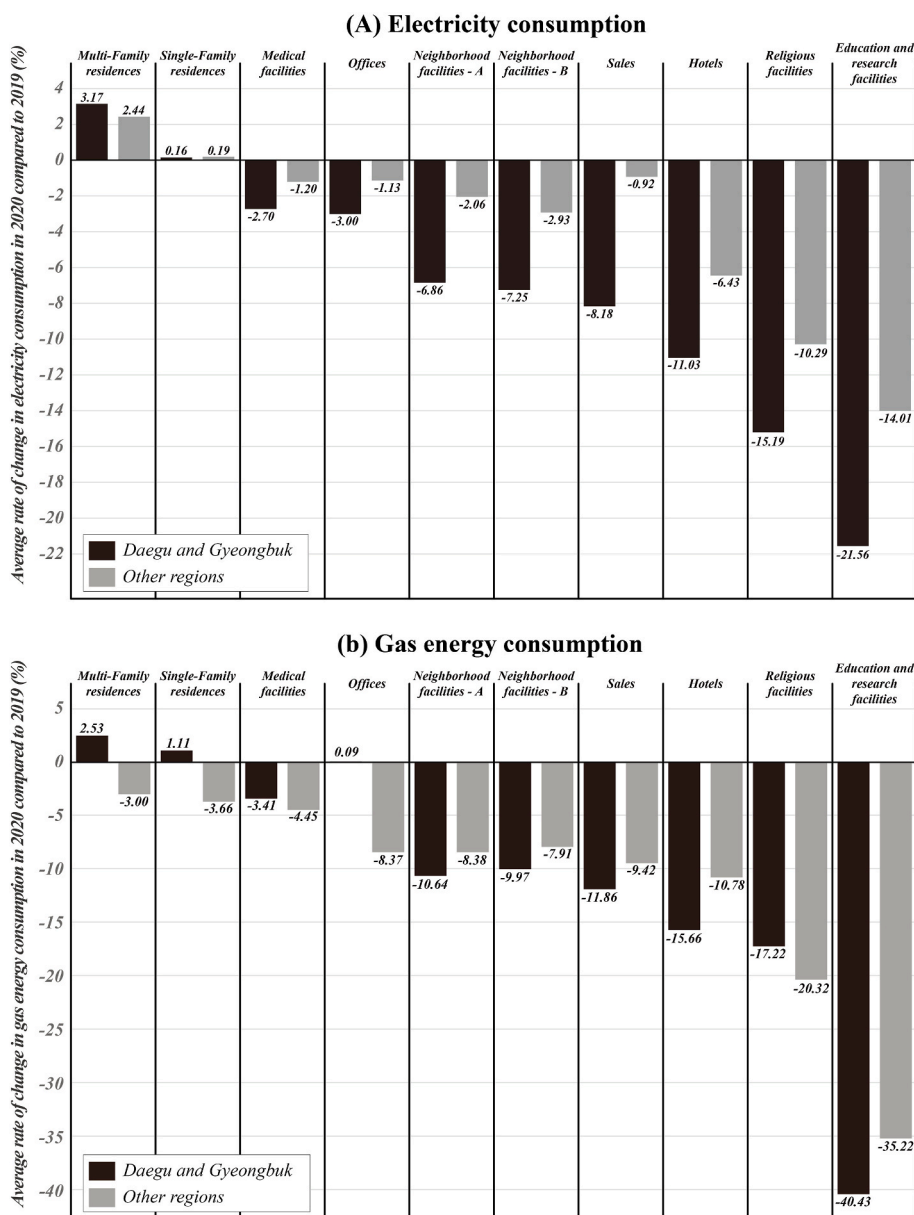


Fig. 3. Average rate of change in energy consumption by building use type according to regional infection of COVID-19.

Daegu, Gyeongbuk, and other regions decreased by 8.61%, 5.10%, and 2.06%, respectively. Moreover, gas energy consumption in Daegu, Gyeongbuk, and other regions decreased by 14.25%, 7.04%, and 8.38%, respectively. Similarly, in the case of neighborhood facilities-B, electricity consumption in Daegu, Gyeongbuk, and other regions decreased by 7.27%, 7.22%, and 2.93%, respectively. Finally, gas energy consumption in Daegu, Gyeongbuk, and other regions decreased by 10.84%, 9.11%, and 7.91%, respectively. Neighborhood facilities are useful facilities that help the residents as they are close to residential areas. These include retail shops, grocery stores, restaurants, pubs, cafés, and community centers, among others. The reason for the energy reduction of these facilities is due to the restriction of the business of high-risk facilities (i.e., shopping centers, restaurants, theaters, etc.) and people’s movement due to social distancing.

In the case of sales, electricity consumption in Daegu, Gyeongbuk, and other regions decreased by 9.41%, 6.95%, and 0.92%, respectively. Moreover, gas energy consumption in Daegu, Gyeongbuk, and other regions decreased by 10.14%, 13.57%, and 9.42%, respectively. In the case of hotels, electricity consumption in Daegu, Gyeongbuk, and other

regions decreased by 11.99%, 10.08%, and 6.43%, respectively. Finally, gas energy consumption in Daegu, Gyeongbuk, and other regions decreased by 16.13%, 15.19%, and 10.78%, respectively. With the increase in coronics in sales facilities and hotels, short-term closure or shortening of business hours, and social distancing have been implemented.

In the case of religious facilities, electricity consumption in Daegu, Gyeongbuk, and other regions decreased by 14.15%, 15.93%, and 10.29%, respectively. Moreover, gas energy consumption in Daegu, Gyeongbuk, and other regions decreased by 15.39%, 19.05%, and 10.78%, respectively. The energy consumption of religious facilities with a high population density decreased as the number of super spreaders were detected in these facilities and the nationwide no-entry ordinance has been enacted.

In the case of educational and research facilities, electricity consumption in Daegu, Gyeongbuk, and other regions decreased by 20.02%, 23.10%, and 14.01%, respectively. Moreover, gas energy consumption in Daegu, Gyeongbuk, and other regions decreased by 38.61%, 42.24%, and 35.22%, respectively. The energy consumption in educational and

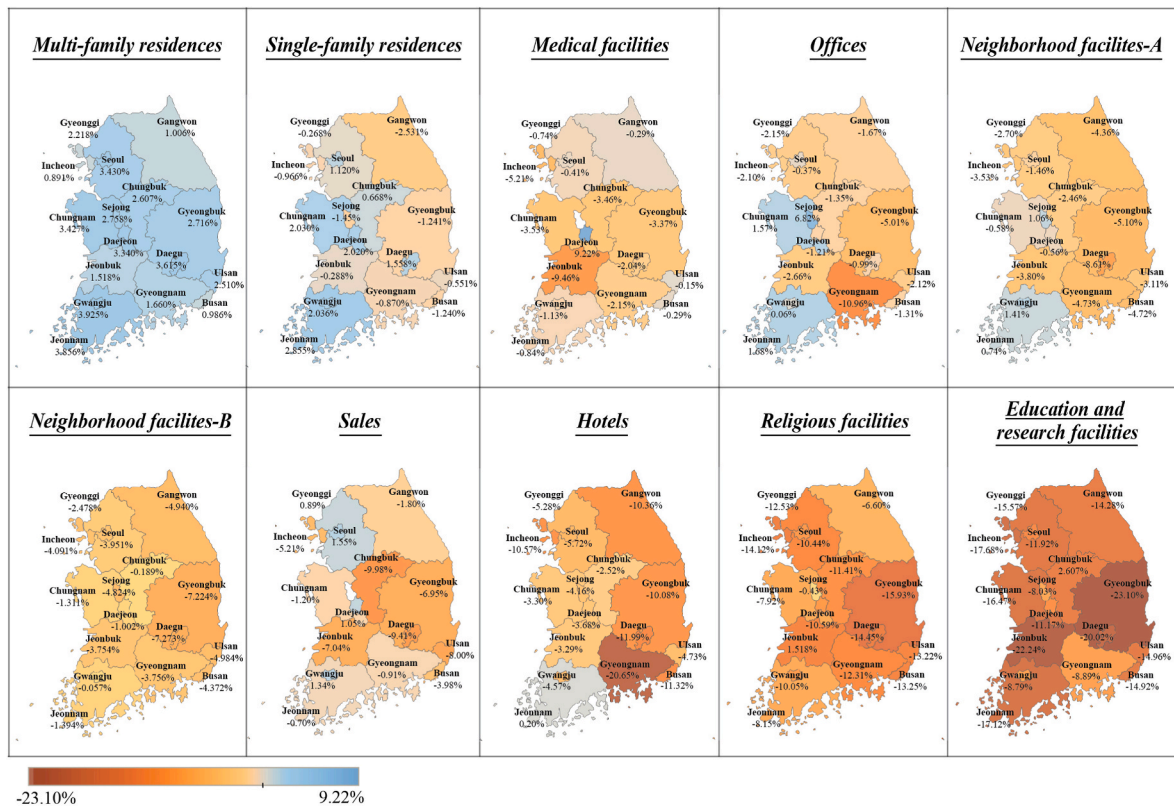


Fig. 4. Regional differences in the rate of change in electricity consumption according to building use type.

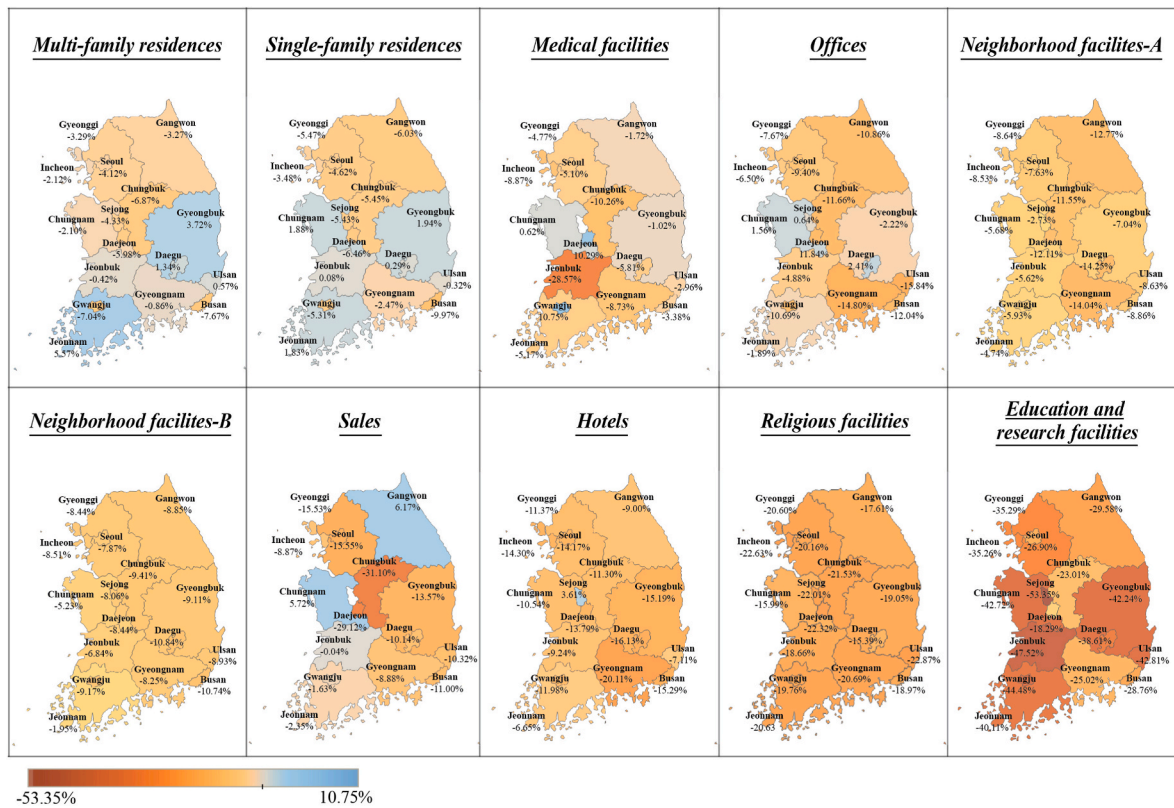


Fig. 5. Regional differences in the rate of change in gas energy consumption according to building use type.

research facilities showed the biggest reduction among all building use types. This is because the South Korean government delayed the term start of schools and conducted online learning to suppress the transmission of coronavirus (refer to Table 1 and Fig. 1).

Compared to the other regions, the change in building energy consumption in Daegu and Gyeongbuk was considerably higher. Compared to the other regions, Daegu and Gyeongbuk experienced cluster infections earlier in February and March than the other regions, so contact and economic activities have been restricted based on the guideline corresponding to social distancing level 2 (refer to Table 1, and Fig. 1).

5. Direction for future energy systems in post COVID-19 era

Based on the results of this study, the sudden COVID-19 crisis threatened the health of the people and caused an economic downturn. However, it has a positive effect on the environment according to this study that the hours of indoor activities of the citizens in residential buildings due to COVID-19 increased in the building energy consumption of the residential facilities. Due to the social distancing during the COVID-19 outbreak in South Korea, the building energy consumption pattern changed, and the rate of change was different for each building use type. For example, it showed that in 2020, the building electricity consumption of educational and research facilities in Gyeongbuk, among all building use types excluding residential facilities, decreased by up to 23.1% compared to 2019. Meanwhile, the building electricity consumption of residential facilities in Gwangju increased by up to 3.9% compared to 2019. These differences in building energy consumption depending on the regional infection situation and building use type can gradually maximize energy demand when COVID-19 is prolonged. Accordingly, this study suggested the future direction for energy policy and system at the community level in the post-COVID-19 era, as follows.

First, since South Korea uses progressive tariffs for electricity consumption in residential buildings, the electricity bills can exponentially soar [75], about three times higher than before as the electricity consumption of residential buildings increases. Therefore, electricity bills should be reduced by offering electricity bill subsidies or adjusting the progressive tariff zone at the residential buildings at the community level. In this regard, the trends of coronics vary by region and, therefore, a suitable amount of subsidy should be offered according to region.

Second, a distributed renewable generation system is essential in unexpected situations where energy usage changes rapidly due to a global pandemic caused by a virus (like a COVID-19) that can happen again at any time [76]. To prevent financial damage to the government and electricity utilities due to subsidies for progressive tariffs [77,78], as an alternative for increasing building energy consumption, installing distributed renewable generation systems should be considered in all buildings at the community level [79]. Accordingly, buildings installed solar PV with a battery energy storage system (BESS) may increase the profit via net-metering or peer-to-peer (P2P) electricity trading. For example, among non-residential buildings (e.g., medical facilities, offices, education facilities, etc.), buildings installed PV system with BESS will consume less energy than before COVID-19, which may use the solar system's generation and store more electricity remaining in the battery. Between the buildings at the community level, energy prosumers of non-residential buildings can have profited by selling remaining electricity stored in BESS to residential buildings with increased electricity consumption. Also, in the case of an increase in building electricity consumption resulting from a pandemic, electricity bills can be reduced by self-consumption [80].

Third, when the building energy suddenly consumes a lot or less by a prolonged outbreak of COVID-19, a home energy management system (HEMS) or a building energy management system (BEMS) can help for improving the efficient use of building energy consumption. According to Jin et al. [81], Luo et al. [82], and Ahmed et al. [83], the introduction of HEMS can help in saving building energy consumption. In addition, Chen et al. [29] showed that approximately 80% of the population is

willing to use HEMS during the COVID-19 pandemic. As a result, the HEMS and BEMS can help save the building energy consumption of an individual and optimize the community-level energy consumption if they are to be implemented in multiple buildings so as to help control future building energy consumption.

6. Conclusion

Based on big data, this study analyzed the relationship between coronics and building energy consumption, as well as identified the changes in building energy consumption according to building use type under COVID-19 in South Korea. As a result, the average rate of changes in electricity and gas energy consumption decreased by -4.46% and -10.35% , respectively, compared to the previous year. The rate of change for building energy was different for each building use type and region where the coronavirus was rampant.

Although this study is a temporary and regional example based on national data, it supported the need to consider building use types to more effectively manage the building energy consumption in unpredictable disaster situations and then suggested future energy systems. To the best of my knowledge, there are no studies that have analyzed the relationship between COVID-19 and building energy consumption. This study has proven for the first time that the energy consumption in most facilities has tended to decrease while energy consumption in residential facilities increased during COVID-19. Moreover, the results of this study can help manage the energy demand at the community level in Post COVID-19. Despite novelty of this study, the climate adjustment analysis of this study has the limitation that the collection period of building energy consumption data that can collect in Korea is only five years (2015–2019). In the future, in order to derive accurate results by minimizing the bias of output data in multi-variate regression, this study should be used the building energy consumption for more than five years in climate adjustment.

Social distancing provided an opportunity to find patterns of building energy consumption with limited activities. Like the suggested future energy policies and systems of Post COVID-19 era in this study (i. e., subsidizing the electricity bill, adjusting the progressive tariff zone of the residential buildings, installing the distributed renewable energy systems with BESS, and managing the energy consumption through HEMS and BEMS), the establishment of new energy strategies for managing the building energy at the community level would be required considering energy demand patterns depending on the building use type and social influencing variables by the virus. Further research will be conducted to better understand the changes in energy consumption under COVID-19, considering all building use types and region differences by using the monthly empirical data for one year.

Author contribution statement

Hyuna Kang, Methodology, Investigation, Conceptualization, Data curation, Visualization, and Writing - Original Draft. Jongbaek An, Investigation, Data curation, Visualization, and Writing - Original Draft. Hakpyeong Kim, Methodology, Data curation, Visualization, and Writing - Original Draft. Changyoon Ji, Conceptualization, Methodology, Data curation, and Writing - Review & Editing. Taehoon Hong, Methodology, Writing - Review & Editing, Visualization, Project administration, Funding acquisition, and Supervision. Seunghye Lee, Project administration, and Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.rser.2021.111294>.

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