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Development of a new energy efficiency rating system for existing residential buildings

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HIGHLIGHTS

- A new energy efficiency rating system for the residential building was developed.
- The incentive and penalty programs were established using an advanced CBR model.
- The new system was established using reasonable and fair standards.
- It allows all residents to voluntarily participate in the energy saving campaign.
- It can be applied to any country or sector in the global environment.

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ABSTRACT

Building energy efficiency rating systems have been established worldwide to systematically manage the energy consumption of existing buildings. This study aimed to develop a new energy efficiency rating system for existing residential buildings from two perspectives: (i) establishment of reasonable and fair criteria for the building energy efficiency rating system; and (ii) establishment of comparative incentive and penalty programs to encourage the voluntary participation of all residents in the energy saving campaign. Based on the analysis of the conventional energy efficiency rating system for existing residential buildings, this study was conducted in five steps: (i) data collection and analysis; (ii) correlation analysis between the household size and the CO_2 emission density (i.e., CO_2 emission per unit area); (iii) cluster formation based on results of the correlation analysis using a decision tree; (iv) establishment of a new energy efficiency rating system for existing buildings; and (v) establishment of incentive and penalty programs using advanced case-based reasoning. The proposed system can allow a policymaker to establish a reasonable and fair energy efficiency rating system for existing residential buildings and can encourage the voluntary participation of all residents in the energy saving campaign.

1. Introduction

The worldwide crisis known as global warming has prompted the enactment of the *United Nations Framework Convention on Climate Change* in Rio de Janeiro, Brazil in June 1992. This was followed by the *Kyoto Protocol* in Kyoto, Japan in December 1997, which regulated the obligatory greenhouse gas (GHG) emissions from industrialized countries (IPCC, 2007; UNFCCC, 1998). It has been reported that in the U.S. and the European Union (EU), two representative countries/regions with GHG emission reduction obligations, about 40% of the total fossil fuel consumption comes from the building sectors (CCC, 2010; DECC, 2012; EIA, 2012; IEA, 2012). Accordingly, the EU approved the *Energy Performance of Building Directive* (EPBD) on December 16, 2002 to strengthen control over the total energy consumption of buildings. In 2007, EPBD adopted a regulation that forces building purchasers and tenants to provide energy performance certificates (EPCs) in the building sale or rental process. The U.K. announced in December 2006 that it would realize its nearly-zero-energy building (nZEB) target on all new homes in the country by 2016 (ECEEE, 2011; GFE, 2010; IRENA, 2012; Sunikka, 2005; ZCH, 2011). The U.S. Department of Energy (DOE) proactively supports research on nZEB (DOE, 2002; NREL, 2006; NSTC, 2008). Thus, the world is enacting building laws related to building energy efficiency or is reforming existing ones for the improvement of the energy performance of buildings (KC, 2012; KME, 2011; MLTM, 2012; NREL, 2009, 2010; RICS, 2009).

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The *Post-Kyoto Protocol* categorizes South Korea as a non-Annex-I country. As of 2011, however, the main index of South Korea's GHG emissions ranks as high as follows: (i) its annual CO_2 emission was determined to be 0.61 billion tons of CO_2 equiv. (ranked 7th in the world); (ii) the increase ratio of its annual CO_2 emission from 1990 to 2011 was 144% (ranked 6th in the world); and (iii) its annual CO_2 emission per gross domestic product was 0.55 t of CO_2 equiv. per thousand U.S. dollars (ranked 12th in the world) (refer to Table S1). Accordingly, the global society is requesting South Korea to follow the obligatory GHG emission regulation (IEA, 2011; UNDP, 2012).

In keeping with such global trend, South Korea has established GHG emission reduction targets by industry. For the building sector, it has established a 26.9% GHG emission reduction target (business-as-usual) (KG, 2011). To achieve this, the country imposed about 50%, 25%, and 25% of the allocation of emission allowances on its existing buildings, new buildings, and improvement of behavior, respectively (MLTM, 2012). The South Korean government enacted and proclaimed in February 2012 the '*Act on the Promotion of Green Buildings*,' based on the country's national vision, '*Low Carbon and Green Growth*.' This move was aimed at the distribution of green buildings that have high new renewable energy use and lower GHG emissions. Having been in effect since February 23, 2013, this act focuses on controlling the GHG emissions of existing buildings. Based on this act, the South Korean government created a new green-building division under the Ministry of Land, Transport, and Maritime Affairs (MLTM) (MLTM, 2012).

Besides the EU, the U.S. and U.K., South Korea is also establishing a building energy efficiency rating system to systematically control the energy consumption and GHG emissions of its existing buildings. However, for such a system to be effective, it should generally satisfy two conditions: (i) the building energy efficiency rating system should be set up based on reasonable and fair standards; and (ii) its implementation should be coupled with the voluntary participation of all the residents. Therefore, this study analyzed the conventional energy efficiency rating system for existing residential buildings based on these two conditions. Based on the analysis results, this study aimed to develop a new energy efficiency rating system for existing residential buildings from two perspectives: (i) establishment of reasonable and fair criteria for the building energy efficiency rating system; and (ii) establishment of comparative incentive and penalty programs to encourage the voluntary participation of all residents in the energy saving campaign. Towards these objectives, the multi-family housing complex was selected as the representative type of existing residential building in South Korea.

2. Conventional energy efficiency rating system for existing residential buildings

2.1. Building energy efficiency rating system

The EU announced EPBD in 2002 to minimize the GHG emissions of its buildings. EPBD defined not only a clause that made the evaluation of the energy performance of new and existing buildings compulsory, but also a clause that made the attachment of EPCs on contract documents during the sale or rental of buildings compulsory. The building energy efficiency rating system defined by EPBD is generally divided into two types: (i) asset rating calculated by the energy demand calculation method based on the characteristics of a building (mainly for new buildings); and (ii) operational rating based on the building's actual energy consumption (mainly for existing buildings).

EBPD is considered a representative green-building policy worldwide. Based on the EBPD guideline, the U.K., Germany, France, etc. established and operated building laws related to building energy efficiency (DCLG, 2012a, b, 2008; IEEP, 2011).

In the case of the EPCs in the U.K., the asset rating based on the government's standard assessment procedure (SAP) for the energy rating of a dwelling is applied for new residential buildings. For existing buildings, however, both the asset rating based on the reduced-data SAP (RdSAP) and the operational rating based on the actual energy consumption are used. Meanwhile, for public buildings, the U.K. issues display energy certificates (DECs), which are applied to the operational rating. DECs offer a standardized value (0–150) for a building's CO_2 emissions, which is categorized into seven grades from A to G (refer to Fig. 1) (CA EPBD, 2011a; Cho, 2010; Song et al., 2010).

As for the EPCs in Germany, both the asset rating and the operational rating are used selectively. Since 2010, all new buildings and large rehabilitation projects of existing buildings have been required to use the asset rating. For large residential buildings, either the asset or operational rating can be selected. Compared to those of other countries, the EPCs of Germany are not represented in a stepped scale but in a continuous scale, resembling the speed meter. For example, the EPC of a residential building is presented in the range of 0–400 $kWh/m^2 \cdot year$. It consists of several types of buildings from the passive house, which is the standard for energy efficiency in a building, resulting in ultra-low energy buildings that require little energy for space heating or cooling (Passive House, 2013), to single-family home which is not refurbished. Also, the EPC of a non-residential building is presented in the range of 0–1000 $kWh/m^2 \cdot year$ (refer to Fig. 2) (CA EPBD, 2011b; Cho, 2010).

Regarding the EPCs in France, the operational rating based on the actual energy consumption is mainly used. It is divided into four types: (i) sale of existing buildings; (ii) rental of residential buildings; (iii) new buildings; and (iv) public buildings. While the EPCs of residential buildings are divided into seven grades from A to G, those of non-residential buildings are divided into nine grades from A to I (CA EPBD, 2011c; Cho, 2010).

The South Korean government hopes to achieve national energy savings and its GHG emission reduction target by promoting

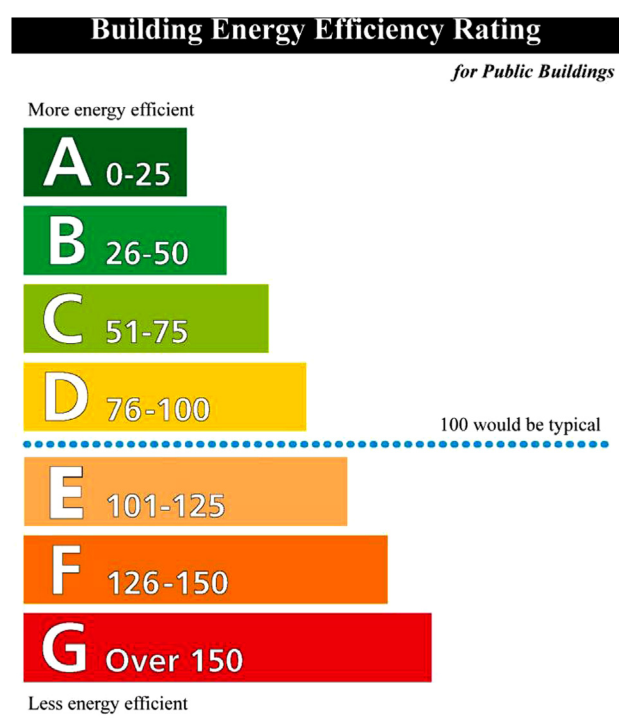

Fig. 1. Building EPCs for the operational rating in the UK.

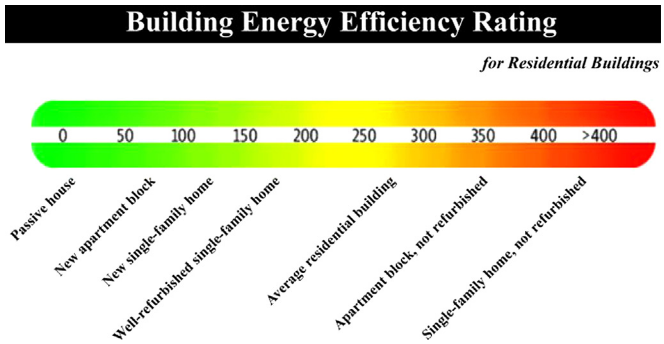

Fig. 2. Building EPCs for the operational rating in Germany.

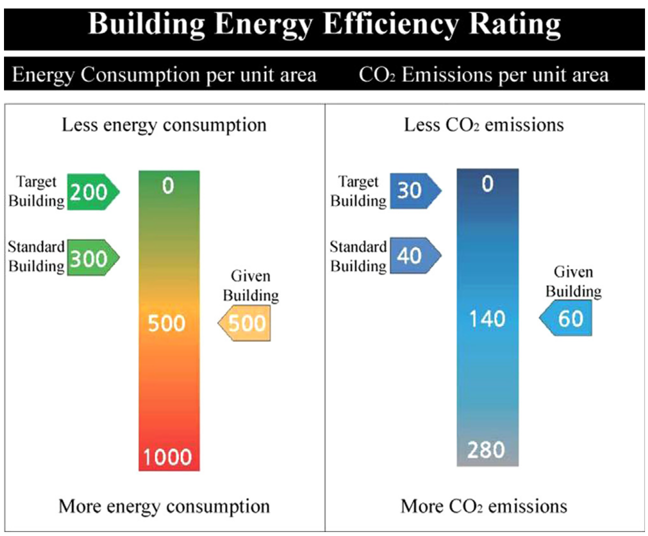

Fig. 3. Building EPCs for the operational rating in South Korea.

improvement of the energy efficiency of the country's existing buildings through the enactment and proclamation of '*the Act on the Promotion of Green Buildings*.' To make the Act effective, the government introduced a building energy certification system, which encourages building purchasers and tenants to select a building with a higher energy performance by attaching building energy certificates to the contract documents in the building sale or rental process. As shown in Fig. 3, the building energy certificates present the operational rating, based on energy consumption and CO_2 emission. Additionally, the average energy consumption of buildings, which is located in the same region and with an identical household size, is presented as a standard value (MLTM, 2012).

As has been discussed, this study examined the current state of the country's implementation of building energy certificates. Conventional building energy certificates have two limitations in their implementation on existing residential buildings: (i) conventional building energy efficiency rating is not based on reasonable and fair standards; and (ii) its implementation is not coupled with the voluntary participation of all the residents.

First, it has been shown that the preliminary survey on the household size was inadequate in establishing the building energy certificates. For residential buildings, the household size is one of the important factors to be considered in determining the building energy efficiency rating. Generally, it is considered that the larger the household size is, the higher the energy consumption per unit area is. However, it is not true.

- Regardless of the household size, the similar sizes of basic home appliances are required. Accordingly, the household size is not directly proportional to the sizes of the home appliances, and neither is the household size directly proportional to the electricity consumptions which are affected by the home appliances (Hong et al., 2012b).
- The household size is highly related to the number of residents. However, because the household size is also related to the income level, it is not directly proportional to the number of residents, and neither is it directly proportional to the heating and cooling energy consumptions which are affected by the number of residents.

Consequently, an increase in the household size tends to decrease the energy consumption per unit area (i.e., the CO_2 emission density or CO_2 emission per unit area, which is commonly used worldwide to determine the building energy efficiency rating). In other words, the smaller the household size is, the lower the building energy efficiency rating can be set. Meanwhile, the larger the household size is, the higher the energy efficiency rating can be set. Therefore, it is necessary to establish a reasonable and fair standard by conducting the correlational analysis between the household size and the CO_2 emission density.

Second, it has been shown that the preliminary survey on the voluntary participation of all residents in the energy saving campaign was shown to be lacking. Additional considerations should be reflected to encourage the voluntary participation of all residents as follows.

- The building energy certificates are attached to the contract documents as part of the building sale or rental process. Accordingly, while the excellent grade in the building energy certificates of a given building can motivate the prospective owners or new tenants of the building to purchase or rent the building, it cannot motivate the existing tenant. In other words, the conventional building energy certificates do not offer additional benefits to the existing tenant based on his or her energy saving efforts. To address this challenge, it is necessary to establish a new incentive and penalty program to promote the existing tenants' voluntary participation in the energy saving campaign.
- In South Korea, the carbon point system is introduced as an incentive program. This conventional incentive program uses the historical energy consumption of a given building (i.e., the monthly average energy consumption for the last two years) as the standard with which to evaluate the GHG reduction. Accordingly, the conventional carbon point system can raise the fairness issues, as follows: (i) the existing residents, who have been already participating in the energy saving campaign, may have a lower energy saving potential; and (ii) the new residents, who do not yet have historical energy consumption, may be excluded from such an incentive program. To address this challenge, it is necessary to establish a comparative incentive and penalty program to encourage the voluntary participation of all residents in the energy saving campaign. The comparative incentive and penalty program can be established by retrieving similar cases based on the characteristics of multi-family housing complexes and by using their annual average energy consumption.

2.2. Literature reviews on the green-building policy

The green-building policy is actively being established worldwide, and various research from diverse viewpoints related to the policy are being conducted. First, many studies have focused on presenting evaluation systems and future improvements of the green-building policy. In Germany, for example, studies have focused on proposing policy improvement plans for the increasing refurbishment rates and energy saving of single-family houses. Towards this end, these studies analyzed the problems of the existing policies in Germany. The following effective policy instruments were proposed: (i) regulatory instruments: random audits, suitable refurbishment occasions; and (ii) financial support instruments: special funding for achieving a high standard of energy efficiency, additional program for supporting measures meeting lower standards and considering the social criteria (income level), additional funding through the existing policy (Weiss et al., 2012). In other studies, the theory-based evaluation method was used, and stakeholder interviews were conducted in order to evaluate policy instruments for improving energy performance of existing private dwellings in the Netherlands. By describing and evaluating the contents, underlying theories, and impacts of the policy instruments, energy policy concepts were established, and the instruments were examined to determine if the following are reflected therein: (i) policy instrument combination; (ii) long-term program; (iii) obligation/incentive balance; (iv) non-generic instruments; (v) primacy to energy efficiency; (vi) whole-house approach; and (vii) energy sufficiency. Results of the research can be the first step towards conceptualizing the improved and alternative policy instruments (Murphy et al., 2012). In the U.K., the limitations of the SAP and RdSAP, tools for building energy performance certification, were analyzed. Results revealed a huge difference between the estimated energy performance resulting from SPA and RdSAP and the actual energy performance. Thus, as part of the improvement plans, Kelly et al. (2012) proposed to add the actual energy consumption to the EPC.

Second, studies have focused on assessing the building energy efficiency rating or the impact of EPCs. For example, in Germany, some studies analyzed the effect of EPCs on the sale of buildings. Using a Web-based survey, these studies showed that the effects of EPCs were limited in the sale of buildings, and argued that the improvement of EPBD would increase the impact of EPCs (Amecke, 2012). In the U.K., studies have focused on the effects of EPCs on the capital and rental values of commercial property assets, using hedonic regression procedures. These have shown that building energy performance did not have a significant relationship with the capital and rental values. In other words, the building energy efficiency rating does not yet affect the market value significantly (Fuerst and McAllister, 2011a). In the U.S., studies have focused on analyzing the effect of eco-labeling on the rental rates, sale prices, and occupancy rates of commercial office buildings, using a hedonic model. In the case of office buildings that have acquired either the Energy Star or Leadership in Energy and Environmental

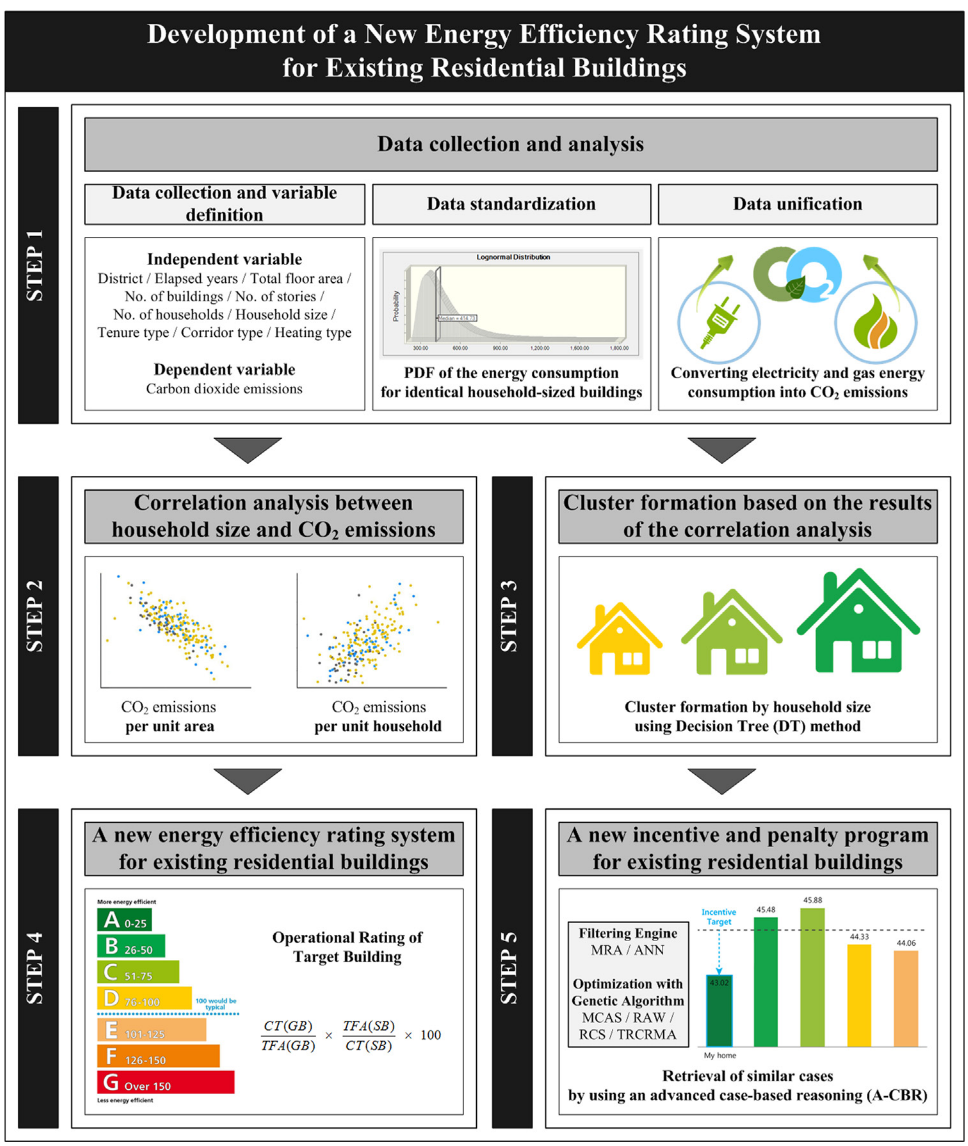

Fig. 4. Research framework.

Design (LEED) eco-labels, the rental and sale price premiums were 3–5% and 18%, respectively, whereas the occupancy premium was negligible. If two certificates were acquired, the rental and sale price premiums were 9% and 25%, respectively (Fuerst and McAllister, 2011b).

Various studies are being conducted on the green-building policy and EPCs. Also, efficient system operation requires improvements of the green-building policy and the building energy efficiency rating, but few studies have proposed concrete improvement plans. Therefore, this study aimed to present a concrete improvement plan for the building energy efficiency rating system and the incentive and penalty programs, which are key issues in the green-building policy, through extensive literature review and data analysis.

3. Research framework

To solve the problems from the conventional energy efficiency rating system and the conventional carbon point system, this study was conducted in five steps: (i) data collection and analysis; (ii) correlation analysis between the household size and the CO_2 emission density; (iii) cluster formation based on the results of the correlation analysis using a decision tree (DT); (iv) establishment of a new energy efficiency rating system for existing residential buildings; and (v) establishment of a new incentive and penalty program for existing residential buildings using advanced case-based reasoning (A-CBR) (refer to Fig. 4).

3.1. Data collection and analysis

3.1.1. Data collection and variable definition

In this research, the multi-family housing complex was selected as the representative type of existing residential building in South Korea. The key energy sources mainly used in residential buildings are electricity, which is used for home appliances, lighting, and cooling; and gas energy, which is used for domestic heating, water heating, and cooking. This energy consumption profile can differ depending on regional characteristics and season (Koo et al., 2014). Therefore, the spatial scope of this study was limited to the multi-family housing complexes located in Seoul, and its temporal scope was limited to the 2010 energy consumption data. A total of 299 complexes with both electricity and gas energy data were used. Table 1 shows the independent variables affecting energy consumption and the explanation of the CO_2 emission density, which was used as a dependent variable in this study. This study used the CO_2 emission density as the assessment standard, which is commonly used worldwide to determine the building energy efficiency rating. Meanwhile, if it is necessary, a better measure might be energy consumption per person (or CO_2 emission per person). However, the available administrative data does not include the private information such as the number of residents and the income level of residents. Given this background, this study determined that energy consumption per unit area might be the best measure.

3.1.2. Data standardization

In spite of their identical household sizes in identical regions, the energy consumption profiles of buildings can differ according to the residential environment and lifestyle of the residents. Thus, to ensure the representative nature of the energy consumption data, this study estimated the probability density function (PDF) on the energy consumption of identical household-sized buildings. To extract the PDF, this study used the "distribution fitting" function of Crystal Ball. The median of such estimated PDF was used as a representative value to minimize the effect of the outlier.

3.1.3. Data unification

To present the grade of energy consumption on the building energy certificate, it is necessary to unify different energy sources (i.e., electricity and gas energy) in a common unit. In other words, they need to be converted into the primary energy consumption or CO_2 emission. To assess the global warming potential, an index most closely related to climate change, this study set the CO_2 emission density as a dependent variable (refer to Table 1). To calculate CO_2 emission by energy source, the following Eqs. (1.1) and (1.2) were used, along with CO_2 emission factor by energy source offered by *Intergovernmental Panel on Climate Change*. Also, based on Eq. (1.3), CO_2 emission as a common unit was calculated.

$$CE\,(tCO_2) = (\text{The yearly amount of electricity consumption (kWh)}) \times \left(\text{Carbon dioxide emission factor for electricity}\left(\frac{tCO_2}{MWh}\right) \times \left(\frac{1}{10}\right)^3\right) \tag{1.1}$$

where, *CE* stands for CO_2 emission for electricity consumption; and CO_2 emission factor for electricity is 0.4705 tCO_2/MWh.

$$CG(tCO_2) = (\text{The yearly amount of gas energy consumption } (m^3)) \times \left(\text{Sensible caloric value for gas energy}\left(\frac{Kcal}{m^3}\right) \times \left(\frac{1}{10}\right)^7\right) \times \left(\text{Carbon emission factor for gas energy}\left(\frac{tC}{TOE}\right)\right) \times \left(\text{The ratio of the molecular weight of } CO_2 \text{ to carbon}\left(\frac{tCO_2}{tC}\right)\right) \tag{1.2}$$

where, *CG* stands for CO_2 emission for gas energy consumption; the sensible caloric value for gas energy is 9420 $Kcal/m^3$; CO_2 emission factor for gas energy is 0.637 tC/TOE; and the ratio of the molecular weight of CO_2 to carbon is 44 tCO_2/12tC.

$$CT\,(tCO_2) = CE\,(tCO_2) + CG\,(tCO_2) \tag{1.3}$$

Table 1
Factors affecting the CO_2 emission density of multi-family housing complex.

Variables		Detailed description	Type of scale
Independent variable	District	25 Districts in Seoul city	Nominal
	Elapsed years	( ) years	Ratio
	Total floor area	( ) m^2	Ratio
	No. of buildings	( ) buildings	Ratio
	No. of stories	( ) stories	Ratio
	No. of households	( ) households	Ratio
	Household size	( ) m^2	Ratio
	Tenure type	Sale	Nominal
	Corridor type	Stair/Corridor/Mixed	Nominal
	Heating type	Individual/Central	Nominal
Dependent variable	CO_2 emission density	( ) $kgCO_2/m^2/yr$	Ratio

where, *CT* stands for CO_2 emission for total energy consumption; *CE* stands for CO_2 emission for electricity; and *CG* stands for CO_2 emission for gas energy.

3.2. Correlation analysis between the household size and the CO_2 emission density

Table 2 shows the results of the correlation analysis between the household size and the CO_2 emission density. The correlation coefficient between the household size and the CO_2 emission density was negative (-0.456), indicating that if the CO_2 emission density will be used as an assessment standard, the smaller the household size is, the higher the CO_2 emission density is. In other words, the smaller the household size is, the lower the building energy efficiency rating can be set. The results indicate that there is the irrationality in the conventional system. To address this problem, this study conducted cluster formation based on the household size so as to establish reasonable and fair criteria for the building energy efficiency rating system.

3.3. Cluster formation based on the results of the correlation analysis

Decision tree (DT), a nonparametric method, performs cluster formation through the correlation analysis between the independent and dependent variables. Its result can then be used in explaining the data structure. The CO_2 emission density as the dependent variable is in continuous scale. Accordingly, this study used CHAID (chi-squared automatic interaction detection) among the various DT methods. As previously discussed, an increase in household size tends to decrease the CO_2 emission density. Thus, in forming a cluster using the DT method, this study attempted to establish a reasonable and fair standard for determining the grade of the building energy certificates, using the household size (one of the independent variables) as the splitting criteria. As shown in Table 3 and Fig. 5, three clusters were formed based on the household size by using the software program called '*IBM SPSS Statistics* 21.0.' Fig. 6 shows the distribution of the CO_2 emission density by cluster. As the data accumulate in the future, more clusters will be formed, which allows multilateral analyses.

3.4. A new energy efficiency rating system for existing residential buildings

In this study, the PDF of the CO_2 emission density was estimated for each of the three clusters. Fig. 7 shows the PDF of the CO_2 emission density for cluster 1. The median value (i.e., 47.59 $kgCO_2/m^2/yr$) of Fig. 7 stands for the CO_2 emission density of the standard building in cluster 1. Namely, it means the typical CO_2 emission density for the buildings included in cluster 1. The PDFs for clusters 2 and 3 are shown in Figs. S1 and S2. According to the U.K.'s DECs and South Korea's building energy efficiency rating system, the operational rating was divided into a total of seven grades in this study (refer to Table 4).

Using Eq. (2), the operational rating of a given building can be determined. For example, if the energy efficiency of a given building is identical to that of the standard building, the operational rating is set to 100. If a given building is a zero energy building, in which no fossil fuels are consumed, and the annual electricity consumption equals annual electricity generation (Marszal and Heiselberg, 2010; NREL, 2006; Torcellini and Crawley, 2006; U.S. DOE, 2002), the operational rating is set to 0. If the energy efficiency of a given building is half that of the standard building, the operational rating is set to 200.

$$OR(GB) = \frac{CT(GB)}{TFA(GB)} \times \frac{TFA(SB)}{CT(SB)} \times 100 \quad (2)$$

where, *OR*(*GB*) stands for the operational rating of a given building; *CT*(*GB*) stands for CO_2 emission density for the total energy consumption of a given building; *TFA*(*GB*) stands for the total floor

Table 2
Correlation analysis between the household size and the CO_2 emission density.

Variable		CO_2 emission density ($kgCO_2/m^2/yr$)
Household size (m^2/class)	Pearson correlation	-0.456**
	Sig. (2-tailed)	0.000
	N	299

**Correlation coefficient is significant at 0.01 level (both sides).

Table 3
Definition of the splitting criteria for the CO_2 emission density.

Cluster	Number of cases	CO_2 emission density ($kgCO_2/m^2/yr$)	Household size (m^2) (X_1)
1	59	48.320	$X_1 \le 96.770$
2	180	45.114	$96.770 < X_1 \le 111.450$
3	60	42.088	$X_1 > 111.450$

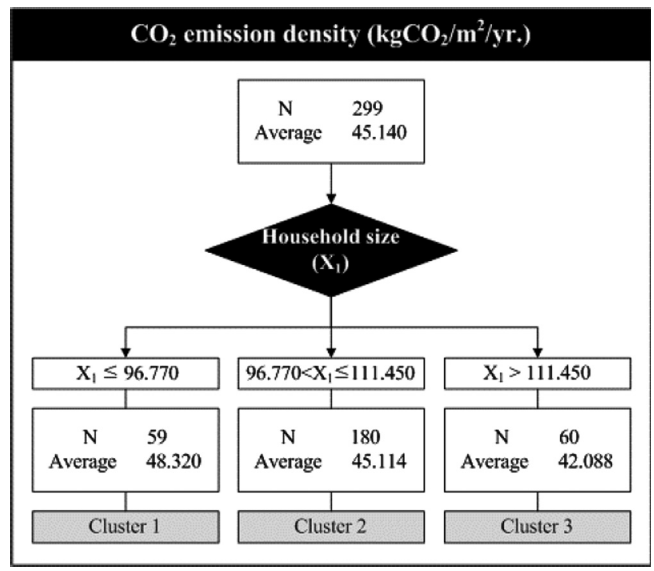

Fig. 5. Cluster formation using a decision tree.

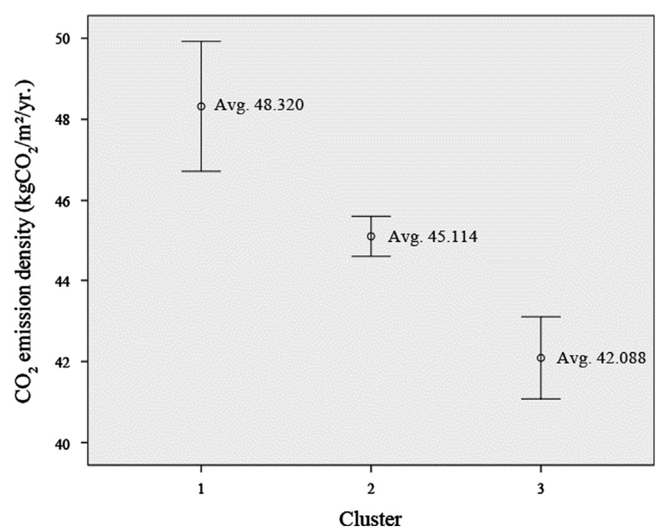

Fig. 6. Distribution of the CO_2 emission density by cluster.

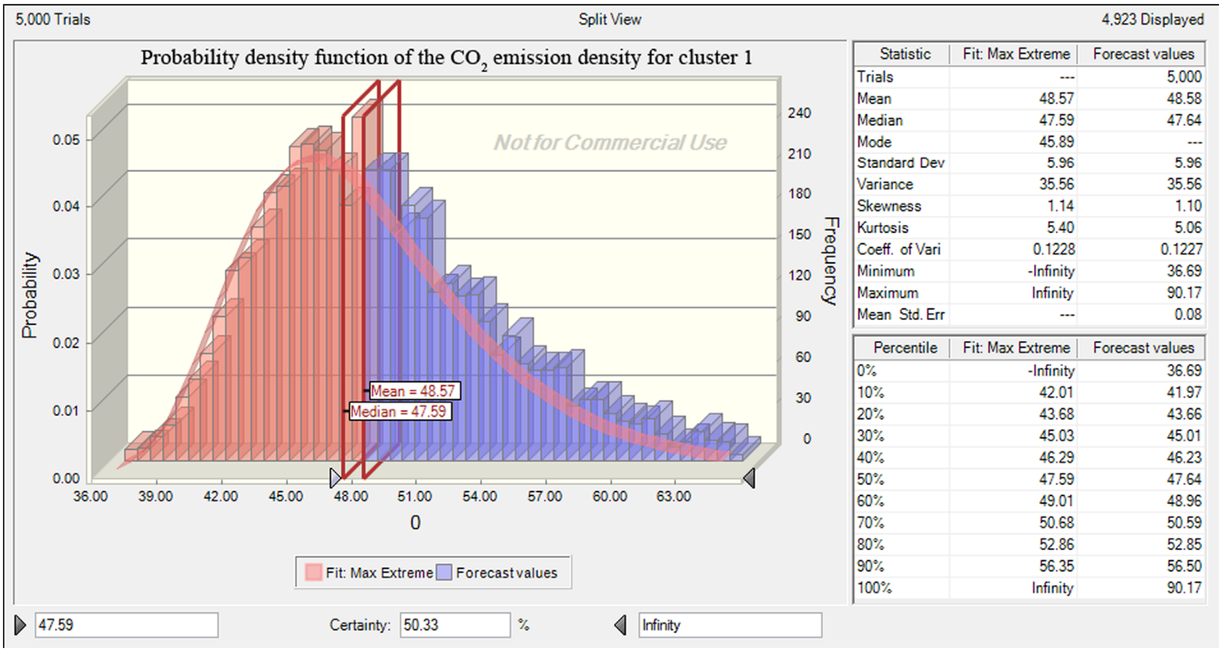

Fig. 7. Probability density function of the CO_2 emission density for cluster 1.

Table 4
Seven grades (A to G) for the operational rating.

Operational rating	'A to G' label
0–25	A
26–50	B
51–75	C
76–100	D
101–125	E
126–150	F
More than 150	G

Note: The standard building has an operational rating of 100.

area of a given building; *TFA*(*SB*) stands for the total floor area of the standard building; and *CT*(*SB*) stands for CO_2 emission density for the total energy consumption of the standard building.

3.5. A new incentive and penalty program for existing residential buildings

Along with the proposed energy efficiency rating system for existing buildings, this study proposed a new incentive and penalty program: the improved carbon point system. The improved carbon point system creates motivation effects not only on the prospective owner or new residents, the ones who are related to the sale or rental of a building, but also on the existing residents, so that they can voluntarily participate in the energy saving campaign.

There currently exists a carbon point system, which is introduced as an incentive program targeting existing residential buildings (Carbon Point System, 2013; Green Credit Card System, 2013; Green Together, 2013; KME, 2012; Lee, 2011). However, this conventional incentive program uses the historical energy consumption of a given building (i.e., the monthly average energy consumption for the last two years) as the standard with which to evaluate the GHG reduction. To address this challenge, it is necessary to establish a comparative incentive and penalty program. Namely, the standard for the incentive and penalty can be established by retrieving similar cases based on the characteristics of multi-family housing complexes and by using their annual average energy consumption. Ultimately, the sustainable and voluntary participation of all residents in the energy saving campaign can be promoted.

To retrieve similar cases, this study used the advanced case-based reasoning (A-CBR) method. The A-CBR model is a hybrid method that combines artificial neural network (ANN), multi-regression analysis (MRA), and genetic algorithm (GA), based on the CBR model that proposes estimation results based on similar cases. The A-CBR model uses a filtering mechanism based on ANN and MRA to complement its weakness: its lower prediction accuracy compared to that of ANN or MRA.

This study developed an A-CBR model for each of the three clusters, using the aforementioned DT method. Fig. S3 shows the detailed process of developing the A-CBR model, and the corresponding equations. More detailed explanations have been given by previous researches (Hong et al., 2014a, b, 2012a, b, c; Koo et al., 2013b, 2011).

3.5.1. Selection of similar cases using CBR

In the CBR method, similar cases can be retrieved based on the case similarity, which is calculated using attribute similarity and attribute weight. It can be expressed as a determinant using

$$\begin{pmatrix} AS_{11} & \cdots & AS_{1n} \\ \vdots & \ddots & \vdots \\ AS_{m1} & \cdots & AS_{mn} \end{pmatrix} \begin{pmatrix} AW_1 \\ \vdots \\ AW_n \end{pmatrix} = \begin{pmatrix} CS_1 \\ \vdots \\ CS_m \end{pmatrix} \tag{3.1}$$

where, *AS* is the attribute similarity; *AW* is the attribute weight; *CS* is the case similarity; *m* is the number of cases; and *n* is the number of attributes.

First, if an attribute is in continuous scale, the attribute similarity can be calculated using Eq. (3.2), when the attribute similarity is more than the minimum criterion for scoring the attribute similarity (MCAS); otherwise, it is 0. On the other hand, if an attribute is in nominal scale, when the value of the attribute is the same, the attribute similarity can be considered 100; otherwise, it is 0. Second, the case similarity can be calculated using Eq. (3.3).

$$f_{AS}(x) = \begin{cases} 100 - \left(\frac{|AV_{Test_Case} - AV_{Retrieved_Case}|}{AV_{Test_Case}} \times 100\right) & \text{if} \quad f_{AS}(x) \geq MCAS \\ 0 & \text{if} \quad f_{AS}(x) < MCAS \end{cases} \tag{3.2}$$

where, f_{AS} is the function of the attribute similarity; $AV_{test\text{-}case}$ is the attribute value of the test case; and $AV_{retrieved\text{-}case}$ is the attribute value of the retrieved case.

$$f_{CS}(x) = \frac{\sum_{i=1}^{n}(f_{AW_i} \times f_{AS_i})}{\sum_{i=1}^{n}(f_{AW_i})} \tag{3.3}$$

where, f_{CS} is the function of the case similarity; f_{AW} is the function of the attribute weight; and n is the number of attributes.

For the similar cases retrieved based on the case similarity, the mean absolute percentage error (MAPE) and the prediction accuracy can be calculated using

$$f_{MAPE}(x) = \frac{100}{m} \times \sum_{i=1}^{m} \left| \frac{AV_i - PV_i}{AV_i} \right| \tag{4.1}$$

$$f_{PA}(x) = 100 - f_{MAPE}(x) \tag{4.2}$$

where, f_{MAPE} is the function of the MAPE; AV is the actual value of the target variable; PV is the predicted value of the target variable; m is the number of cases; and f_{PA} is the function of the prediction accuracy.

3.5.2. A filtering mechanism for improving the prediction accuracy

In the CBR method, the relationship between the case similarity and the prediction accuracy is not always proportional. Accordingly, it is necessary to establish a filtering mechanism for improving prediction accuracy. In this study, a filtering mechanism was developed using the ANN and MRA models. It can be expressed using Eqs. (5.1)–(5.4). The CBR model with a filtering mechanism was defined as an A-CBR model.

$$PV_{ANN} \times \left(1 - \frac{MAPE_{ANN}}{100}\right) \leq PR_{ANN} \leq PV_{ANN} \times \left(1 + \frac{MAPE_{ANN}}{100}\right) \tag{5.1}$$

$$PV_{MRA} \times \left(1 - \frac{MAPE_{MRA}}{100}\right) \leq PR_{MRA} \leq PV_{MRA} \times \left(1 + \frac{MAPE_{MRA}}{100}\right) \tag{5.2}$$

where, PR_{ANN}, PV_{ANN}, and $MAPE_{ANN}$ stand for the predicted range, the predicted value, and the MAPE of the ANN model, respectively; and PR_{MRA}, PV_{MRA}, and $MAPE_{MRA}$ stand for the predicted range, the predicted value, and the MAPE of the MRA model, respectively.

$$Max(Min(PR_{ANN}), Min(PR_{MRA})) \leq CRMA \leq Min(Max(PR_{ANN}), Max(PR_{MRA})) \tag{5.3}$$

$$Min(CRMA) \times \left(1 - \frac{TRCRMA}{100}\right) \leq CRMA^* \leq Max(CRMA) \times \left(1 + \frac{TRCRMA}{100}\right) \tag{5.4}$$

where, $CRMA$ is the cross-range between the predicted value of the MRA and ANN models; $TRCRMA$ is the tolerance range of the CRMA; and $CRMA^*$ is the filtering range in which the TRCRMA was applied to the CRMA.

3.5.3. Establishment of the optimization process by using GA

In the A-CBR model, a total of four optimization parameters were applied to maximize prediction accuracy: (i) MCAS; (ii) RAW (the range of the attribute weight); (iii) TRCRMA; and (iv) RCS (the range of the case selection). To find the optimal solution of the four parameters, this study established the optimization process using GA.

4. Results and discussion

4.1. A new energy efficiency rating system for existing residential buildings

This study proposed an improvement plan for the conventional energy efficiency rating system for existing residential buildings. As shown in the analysis results in Section 3.2, there is the irrationality in the conventional system. To address these issues, this study conducted cluster formation based on the household size (refer to Table 3). The results of the comparative analysis between the conventional system (i.e., the overall-data-based energy efficiency rating) and the proposed system (i.e., the cluster-based energy efficiency rating) were shown in Table 5, Figs. 8, and S4. The following is a discussion of the changes that occurred in the energy efficiency rating by cluster.

First, it was determined that the overall energy efficiency rating of the small-household-sized building (included in cluster 1) was adjusted upward. As shown in the third column (A) and the sixth column (D) of Table 5, it was determined that the average of the operational rating in the proposed system (101.5, dark blue line of Fig. 8) was decreased by 5.7 points, compared to that in the conventional system (107.2, light blue line of Fig. 8). In addition, as shown in the fifth column (C) and the eighth column (F) of Table 5, it was determined that the ratio of the cases included in grade A to D was increased from 27.1% (the conventional system) to 57.6% (the proposed system). In conclusion, the overall energy efficiency rating in cluster 1 was adjusted upward.

Second, it was determined that the change in the overall energy efficiency rating of medium-household-sized building (included in cluster 2) was insignificant. As shown in the third column (A) and the sixth column (D) of Table 5, it was determined that the average of the operational rating in the proposed system (99.8, dark green line of Fig. 8) was changed at 0.3 points, compared to that in the conventional system (100.1, light green line of Fig. 8). In addition, as shown in the fifth column (C) and the eighth column (F) of Table 5, it was determined that the ratio of the cases included in grade A to D was changed from 50.0% (the conventional system) to 50.6% (the proposed system). In conclusion, there was no significant change in the energy efficiency rating in cluster 2.

Third, it was determined that the overall energy efficiency rating of the large-household-sized building (included in cluster 3) was adjusted downward. As shown in the third column (A) and the sixth column (D) of Table 5, it was determined that the average of the operational rating in the proposed system (100.1, dark red line of Fig. 8) was increased by 6.8 points, compared to that in the conventional system (93.3, light red line of Fig. 8). In addition, as shown in the fifth column (C) and the eighth column (F) of Table 5, it was determined that the ratio of the cases included in grade A to D was decreased from 80.0% (the conventional system) to 46.7% (the proposed system). In conclusion, the overall energy efficiency rating in cluster 3 was adjusted downward.

In summary, it was determined that the irrationality of the conventional energy efficiency rating (which was caused by the negative correlation between the household size and the CO_2 emission density) had been resolved. Namely, in the conventional system (refer to the fifth column (C) of Table 5), the small-household-sized building (included in cluster 1) has a higher CO_2 emission density just because it has a small area; accordingly, it has a lower energy efficiency rating. Meanwhile, the large-household-sized building (included in cluster 3) has a lower CO_2

Table 5
Comparison results of the conventional system and proposed system.

Classification			Conventional system			Proposed system		
Cluster	A to G label		Sum of the operational rating	The number of cases	Ratio (%)	Sum of the operational rating	The number of cases	Ratio (%)
			(A)	(B)	(C)	(D)	(E)	(F)
Cluster 1	A	0–25	0.0	0	27.1%	0.0	0	57.6%
(Small household size)	B	26–50	0.0	0		0.0	0	
	C	51–75	0.0	0		0.0	0	
	D	76–100	1516.3	16		3190.3	34	
	E	101–125	4104.7	38	72.9%	2375.5	22	42.4%
	F	126–150	389.7	3		273.4	2	
	G	More than 150	312.0	2		151.3	1	
	Sum		6322.7	59	–	5990.6	59	–
	Average		107.2	–	–	101.5	–	–
Cluster 2	A	0–25	0.0	0	50.0%	0.0	0	50.6%
(Medium household size)	B	26–50	0.0	0		0.0	0	
	C	51–75	136.9	2		136.6	2	
	D	76–100	8386.3	88		8467.7	89	
	E	101–125	9359.8	89	50.0%	9239.2	88	49.4%
	F	126–150	126.7	1		126.4	1	
	G	More than 150	0.0	0		0.0	0	
	Sum		18,009.7	180	–	17,969.8	180	–
	Average		100.1	–	–	99.8	–	–
Cluster 3	A	0–25	0.0	0	80.0%	0.0	0	46.7%
(Large household size)	B	26–50	0.0	0		0.0	0	
	C	51–75	73.0	1		0.0	0	
	D	76–100	4271.7	47		2584.6	28	
	E	101–125	1255.8	12	20.0%	3289.6	31	53.3%
	F	126–150	0.0	0		132.6	1	
	G	More than 150	0.0	0		0.0	0	
	Sum		5600.6	60	–	6006.9	60	–
	Average		93.3	–	–	100.1	–	–

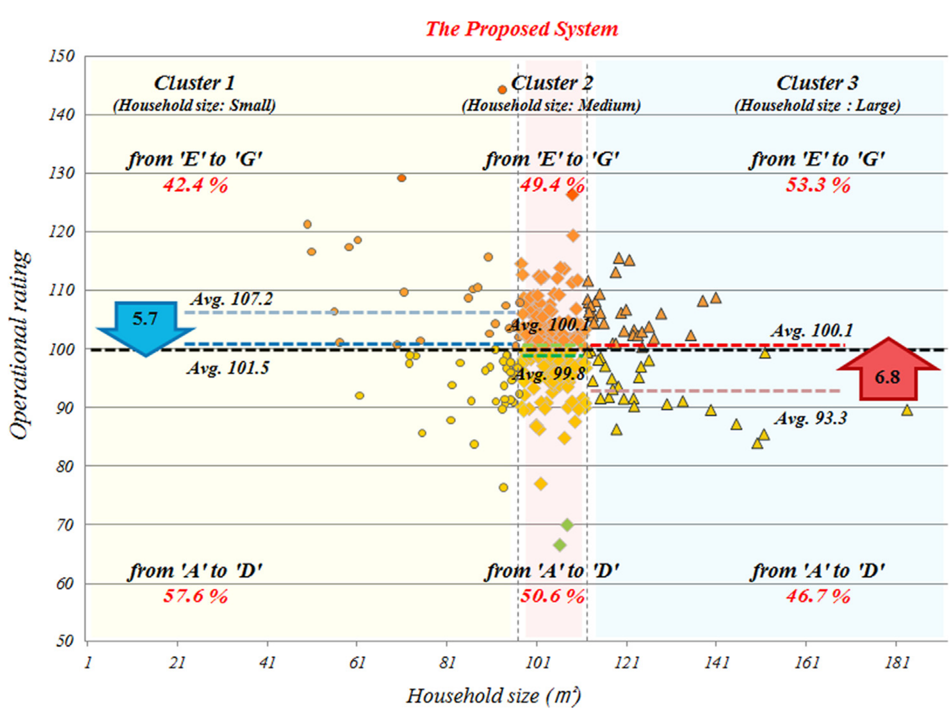

Fig. 8. Distribution of the operational rating by cluster in the proposed system. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article).

emission density just because it has a larger area; accordingly, it has a higher energy efficiency rating. These results are caused by the irrationality of the conventional system. To address this challenge, this research proposed the cluster-based energy efficiency rating system. Through the application of the proposed system (refer to the eighth column (F) of Table 5), the overall

Table 6
Comparison of prediction accuracy and standard deviation by model.

Model	Cluster 1		Cluster 2		Cluster 3	
	APA[a]	SDPA[b]	APA	SDPA	APA	SDPA
MRA	93.25	5.89	95.55	5.27	93.73	4.86
ANN	93.18	6.26	95.68	4.40	94.69	4.37
CBR	90.72	7.93	93.50	5.89	92.25	6.85
A-CBR	94.02	5.96	96.58	4.10	94.92	4.31

Note:
[a] APA stands for the average prediction accuracy.
[b] SDPA stands for the standard deviation of the prediction accuracy.

energy efficiency rating of small-household-sized building (included in cluster 1) was adjusted upward (101.5), compared to that in the conventional system (107.2). Meanwhile, the overall energy efficiency rating of large-household-sized building (included in cluster 3) was adjusted downward (100.1), compared to that in the conventional system (93.3). Therefore, it was concluded that the reasonable and fair criteria for the building energy efficiency rating system had been established in this study.

4.2. A new incentive and penalty program for existing residential buildings

This study proposed an incentive and penalty program – the carbon point system – to encourage the prospective owner or new residents as well as the existing residents to voluntarily participate in the energy saving campaign. This study proposed an A-CBR model as the reasonable standard with which to set the GHG emissions reduction in carbon point system.

4.2.1. Validation of the prediction accuracy of the A-CBR model

To validate the prediction performance of the A-CBR model, this study compared the proposed model to the other models which were often used in previous researches: the ANN, MRA, and CBR models.

Table 6 shows the average prediction accuracy and the standard deviation of the prediction accuracy for each of the three clusters. The average prediction accuracy of the A-CBR model in all the three clusters was superior to the other models (about 95%): 94.02% for cluster 1, 96.58% for cluster 2, and 94.92% for cluster 3. Also, the standard deviation of the prediction accuracy was superior to the other model (about 5%) in all the three clusters: 5.96% for cluster 1, 4.10% for cluster 2, and 4.31% for cluster 3. Compared to the MRA, ANN, and CBR models, it was determined that the prediction performance was improved with the use of the A-CBR model.

It was determined that the A-CBR model obtained the advantage of the CBR model, which offers historical cases as the bases for decision making processes, and that of the ANN model, which has excellent prediction accuracy. Therefore, the A-CBR model is believed to be suitable for use as an incentive and penalty standard.

4.2.2. Application of the new incentive and penalty program

Based on the proposed energy efficiency rating system for existing residential buildings, this study divided the targets applicable to the incentive and penalty program into seven grades of operational rating. As shown in Table 4, the seven grades of operational rating were calculated based on Eq. (2). If the energy efficiency of a given building is identical to that of the standard building, the operational rating is set to 100. Therefore, compared to the standard building, the buildings whose energy efficiency is

Table 7
Characteristics of the five cases retrieved using the A-CBR model for an incentive program.

Class	Case no.	District no.	Elapsed year	Total floor area (m²)	No. of buildings	No. of stories	No. of households	Household size (m²)	Tenure type	Corridor type	Heating type	CO_2 emission density ($kgCO_2/m^2$)	OR[a]	Grade	CS[b] (%)	PA[c] (%)
TC[d]	168	25	10	17,407	1	19	172	101.20	1	3	1	43.02	95.19	D	–	–
RC[e] 1	174	25	13	17,264	2	20	169	102.15	1	3	1	45.48	100.64	E	68.79	94.59
RC[e] 2	177	25	12	26,808	2	19	266	100.78	1	3	1	45.88	101.53	E	52.31	93.76
RC[e] 3	169	25	11	30,119	2	19	286	105.31	1	3	1	44.33	98.09	D	42.58	97.04
RC[e] 4	155	25	11	22,752	1	18	235	96.82	1	3	1	44.06	97.50	D	41.63	97.63
RC[e] 5	82	16	11	33,407	2	18	332	100.62	1	3	1	45.09	99.77	D	41.48	95.41

Note:
[a] OR stands for the operational rating.
[b] CS stands for the case similarity.
[c] PA stands for the prediction accuracy.
[d] TC stands for the test case.
[e] RC stands for the retrieved case.

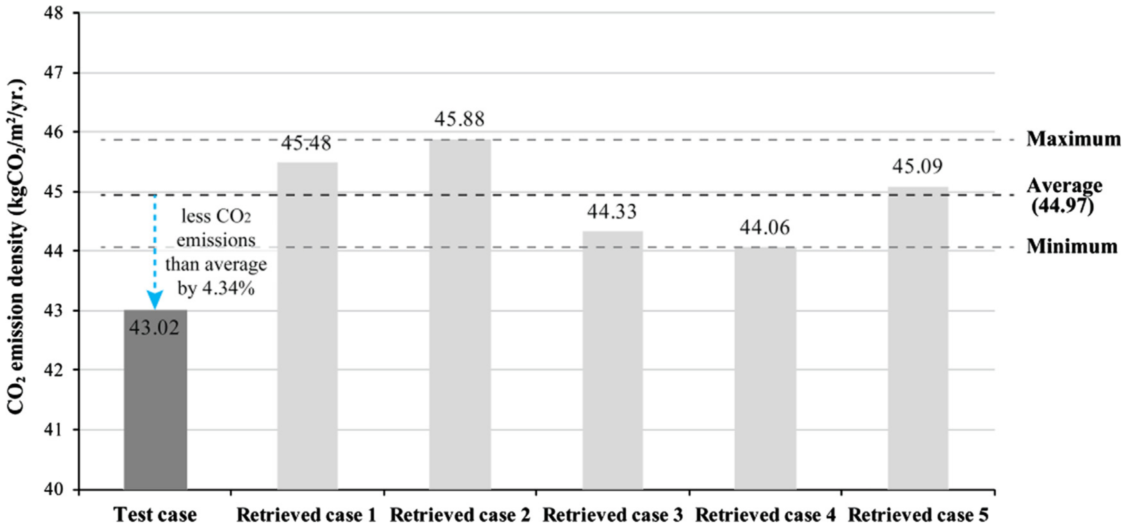

Fig. 9. Comparison of the CO_2 emission density of the test case and retrieved cases for an incentive program.

excellent (grade A, B, C, or D) were categorized as target buildings for incentive programs. On the other hand, the buildings whose energy efficiency grade is inferior (grade E, F, or G) were categorized as target buildings for penalty programs.

First, the application from the perspective of the new incentive program was conducted using the test case included in label D. Table 7 shows the characteristics of the test case and the five cases retrieved using the A-CBR model. Fig. 9 shows the CO_2 emission density of the test case and the five cases retrieved using the A-CBR model. It was shown that the CO_2 emission density of the test case (43.02 $kgCO_2/m^2$) was lower by 4.34%, compared to the average value of the five retrieved cases (44.97 $kgCO_2/m^2$). In other words, the test case can obtain a carbon point of 4.34 (savings rate) as an incentive, as opposed to the similar cases. If the test case is applied to the conventional carbon point system which is based on the historical energy consumption, the test case is not able to obtain such carbon point because its energy saving potential is very small. This result means that there is the irrationality of the conventional carbon point system.

Second, the application from the perspective of the new penalty program was conducted using the test case included in label E. Table 8 shows the characteristics of the test case and the five cases retrieved using the A-CBR model. Fig. 10 shows the CO_2 emission density of the test case and the five cases retrieved using the A-CBR model. It was shown that the CO_2 emission density of the test case (49.16 $kgCO_2/m^2$) was higher by 5.49%, compared to the average value of the five retrieved cases (46.60 $kgCO_2/m^2$). In other words, the test case should turn in a carbon point of 5.49 (excess rate) as a penalty, compared to the similar cases. If the test case is applied to the conventional carbon point system which is based on the historical energy consumption, the test case is not able to turn in the carbon point because its energy saving potential is very large. This result means that there is the irrationality of the conventional carbon point system.

In summary, it was determined that the irrationality of the conventional carbon point system, which is based on the historical energy consumption of the test case, had been resolved. Namely, in the conventional system, the large-household-sized building has a lower CO_2 emission density just because it has a larger area; thus, it will get the more carbon point. In addition, the existing residents, who have been already participating in the energy saving campaign, may have a lower energy saving potential. Also, the new residents, who do not yet have historical energy consumption, may be excluded from such an incentive program. Therefore, the conventional carbon point system is not able to encourage the voluntary participation of the prospective owner or new residents as well as the existing residents in the energy saving campaign. To address this challenge, this research proposed a comparative incentive and penalty program as a reasonable and fair standard. It can be established by retrieving similar cases based on the characteristics of multi-family housing complexes and by using their annual average energy consumption. In conclusion, the proposed carbon point system as a comparative incentive and penalty program can solve the irrationality of the conventional carbon point system; thus, it can encourage the voluntary participation of the prospective owner or new residents as well as the existing residents in the energy saving campaign.

4.3. EPCs of the proposed system

As shown in Fig. 11, new building energy performance certificates were created based on the proposed energy efficiency rating system and the proposed carbon point system.

In part (1), the operational system based on the actual energy consumption of a given building is presented. As an index comparable to the energy efficiency of the standard building (refer to Section 3.4), a relative grade based on 100 as the standard value is shown. The smaller the operational rating is, the higher the energy efficiency of the building is. As shown in part (1), the operational rating of the given building was 95.19, which is grade D. Compared to the standard building, the energy efficiency of the given building is higher somewhat.

In part (2), the CO_2 emission by energy source, which is consumed by a given building, is presented. If new renewable energy is used, the CO_2 emission reduction is shown at the same time. Also, the CO_2 emission density in the current year (2010) and in the previous year (2009) is presented, through which the history of the CO_2 emission density of the given building can be determined at once.

Finally, in part (3), through comparison with buildings whose characteristics are similar to those of the given building, the carbon point system as an incentive and penalty program is presented. Carbon points can be used in the following ways: (i) as a cash benefit through mileage accumulation; (ii) for deductions in maintenance costs of multi-family housing complexes; (iii) as technical support fund for energy saving; (iv) as

Table 8
Characteristics of the five cases retrieved using the A-CBR model for a penalty program.

Class	Case no.	District no.	Elapsed year	Total floor area (m²)	No. of buildings	No. of stories	No. of households	Household size (m²)	Tenure type	Corridor type	Heating type	CO_2 emission density ($kgCO_2/m^2$)	OR[a]	Grade	CS[b] (%)	PA[c] (%)
TC[d]	77	16	6	74,083	15	18	759	97.61	1	1	1	49.16	108.78	E	–	–
RC[e] 1	100	17	5	78,755	15	20	783	100.58	1	1	1	46.13	102.07	E	58.01	93.43
RC[e] 2	133	18	15	82,564	7	18	782	105.58	1	1	1	46.06	101.92	E	57.46	93.27
RC[e] 3	105	17	4	74,088	11	20	740	100.12	1	1	1	46.59	103.10	E	45.46	94.49
RC[e] 4	88	16	6	28,237	4	19	286	98.73	1	1	1	48.07	106.38	E	41.79	97.74
RC[e] 5	109	17	5	75,619	9	23	747	101.23	1	3	1	46.16	102.14	E	30.00	93.49

Note:
[a] OR stands for the operational rating.
[b] CS stands for the case similarity.
[c] PA stands for the prediction accuracy.
[d] TC stands for the test case.
[e] RC stands for the retrieved case.

technical support fund for the use of new renewable energy; and (v) as contributions to slowing down climate change and to environmental protection. The detailed applications of the carbon points are out of this study's scope, however, and will be discussed in depth in future research.

5. Conclusions

Building energy efficiency rating systems have been established worldwide to systematically manage the energy consumptions and GHG emissions of existing buildings. As the building energy certificates are attached to the contract documents as part of the building sale or rental process, the excellent grade in the building energy certificates of a given building can motivate the prospective owners or new tenants of the building to purchase or rent the building. To achieve this objective, the reasonable and fair criteria for the building energy efficiency rating system should be established.

Based on the analysis of the conventional building energy certificates, this study aimed to develop a new energy efficiency rating system for existing residential buildings from two perspectives: (i) establishment of reasonable and fair criteria for the building energy efficiency rating system; and (ii) establishment of comparative incentive and penalty program to encourage the voluntary participation of all residents in the energy saving campaign. The multi-family housing complex was selected as the representative type of existing residential building in South Korea, and the corresponding data were collected from a total of 299 complexes. The results of this study are summarized as follows.

• First, the correlation between the household size and the CO_2 emission density was negative (-0.456), indicating that there is the irrationality in the conventional energy efficiency rating system. Namely, in the conventional system, the small-household-sized building has a higher CO_2 emission density just because it has a small area; accordingly, it has a lower energy efficiency rating. Meanwhile, the large-household-sized building has a lower CO_2 emission density just because it has a larger area; accordingly, it has a higher energy efficiency rating. These results are caused by the irrationality of the conventional system. To address this problem, this study conducted cluster formation based on the household size as the splitting criteria so as to establish reasonable and fair criteria for the building energy efficiency rating system.

• Second, this study conducted the comparative analysis between the conventional energy efficiency rating system (i.e., the overall-data-based energy efficiency rating) and the proposed system (i.e., the cluster-based energy efficiency rating). Using the proposed system, the overall energy efficiency rating of small-household-sized buildings was adjusted upward, while that of large-household-sized buildings was adjusted downward. Namely, it was determined that the conventional energy efficiency rating's irrationality due to the negative correlation between the household size and the CO_2 emission density had been resolved. Therefore, it was concluded that the reasonable and fair criteria for the building energy efficiency rating system had been established in this study.

• Third, the large-household-sized building has a lower CO_2 emission density just because it has a larger area; thus, it will get the more carbon point. However, this is caused by the irrationality of the conventional carbon point system, which is based on the historical energy consumption. Namely, in the conventional system, the existing residents, who have been already participating in the energy saving campaign, may have a lower energy saving potential. Also, the new residents, who do not yet have historical energy consumption, may be excluded from such an incentive program. To address this problem, this study developed the A-CBR

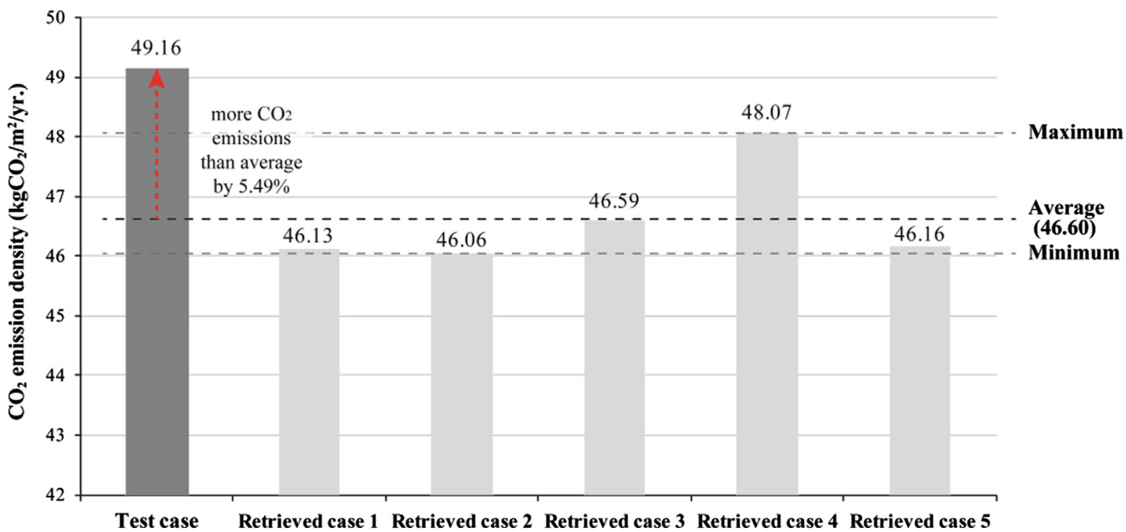

Fig. 10. Comparison of the CO_2 emission density of the test case and retrieved cases for a penalty program.

Fig. 11. Building EPCs of the proposed system.

model that can be used to establish the comparative incentive and penalty program as a reasonable and fair standard. It was aimed not only to solve the fairness issue raised from the conventional carbon point system but also to encourage the voluntary participation of the prospective owner or new residents as well as the existing residents in the energy saving campaign.

Meanwhile, there are some limitations of this research. However, they can be improved or solved through the future research: (i) the proposed system was developed using Microsoft-Excel-based VBA. If it can be developed as the network-based real time system in the future research, it is expected that it can be more useful for practical purposes, offer a systematic and continuous management foundation as a platform, and encourage the voluntary participation of the public in the energy saving campaign; and (ii) this study presented the examples using the carbon point system. If the specific applications of the incentive and penalty program can be presented in the future, it will allow a policymaker to establish a reasonable and fair energy efficiency rating system for existing residential buildings.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.enpol.2013.12.068.

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