Prediction Equations for Energy Consumption Through Surveys on Energy Consumption in Apartment Buildings

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Abstract

This study presents energy consumption prediction equations developed by conducting multiple regression analyses of data collected in surveys of actual states of energy consumption in apartment buildings in their operational stage.

Surveys of actual states of average energy consumption per unit show that 1) the largest component of energy consumption is room heating, followed by electricity, hot water supply, and gas, in that order; 2) energy consumption increases with household area; 3) among exposures, energy consumption is highest in households facing east or northeast and lowest in those facing south or southwest; 4) among height types, energy consumption is highest in super-high-rise apartment buildings (50 stories or higher), followed by semi-super-high-rises, high-rises, and medium-high-rises, in that order; and 5) among plan types, tower-type apartment buildings use approximately 17% – 20% more energy than flat types.

The goodness-of-fit criterion stated in the 2009 ASHRAE Fundamentals Handbook (SI) Edition is shown to be satisfied for the equations presented in this paper for the prediction of energy consumption of apartment buildings in their operational stage. These equations were developed through multiple regression analysis using the areas and heat transmission coefficients of structures as independent variables and using energy consumption as the dependent variable.

Keywords: apartment buildings; energy consumption survey; shading analysis simulation; prediction equation for energy consumption

1. Introduction

At present, the energy used in buildings accounts for approximately 19.8% of domestic energy consumption (Energy Saving Statistics Handbook, http://www.kemco.or.kr), and apartment buildings account for approximately 36% of all energy consumption by buildings (Korea Energy Economics Institute Statistical Information System, http://www.keei.re.kr). Therefore, reducing the energy consumption of apartment buildings is more important now than ever before.

In this study, the energy consumption characteristics of apartment buildings were analyzed, and an energy consumption prediction equation was developed through multiple regression analysis of data collected from surveys of actual states of energy consumption in apartment buildings in their operational stage.

This study will ultimately provide basic data for reduction of energy consumption in buildings by identifying objective information on energy consumption that can be used in the early stages of designing apartment buildings.

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This study consisted of the following steps:

(1) Review of previous studies and theories: Previous studies and theories related to the subject of this study were reviewed.

(2) Analysis of apartment buildings' energy consumption characteristics: Apartment buildings' energy consumption characteristics were analyzed. In particular, considering the fact that energy consumption patterns vary with the shapes of apartment buildings, shading characteristics that depend on the shape of apartment buildings were analyzed through simulations.

(3) Survey of actual states of energy consumption in apartment buildings in their operational stage: Actual states of energy consumption in apartment buildings in the downtown area of Seoul in their operational stage were determined. Quantitative data on the present states of energy consumption with respect to energy items, household areas, exposures, heights, and apartment building types were analyzed to obtain objective information on energy consumption.

(4) Development of an energy consumption prediction equation for apartment buildings: An energy consumption prediction equation was developed through multiple regression analysis, with apartment buildings' energy consumption elements treated as independent variables and the apartment buildings' energy consumption determined from actual state surveys treated as the dependent variable.

2. Review of Previous Studies and Theories

Studies of apartment buildings' energy consumption in Korea have primarily been conducted on room heating energy, excluding room cooling. Kang Jae-Sik (1995) surveyed the actual state of apartment buildings' room heating operations through site and model measurements and computer simulations. Park Yu-Gwon (2003) analyzed differences in energy consumption with respect to household location to examine the problem of thermal imbalance in buildings. Choi Won-Gi *et al.* (2007) analyzed energy consumption patterns with respect to household locations to examine the energy transmitted by adjacent households. Kim Jin-Gwan (2008) examined the actual state of city gas consumption in apartment buildings.

Among the studies of apartment buildings' energy consumption that have been conducted in various countries are studies that have analyzed the energy consumption of apartment buildings in Korea. Hae Jin Kang and Eon Ku Rhee (2012) analyzed energy consumption patterns in "A Development of Energy Load Prediction Equations for Multi-Residential Buildings in Korea." In "Prediction of Residential Building Energy Consumption in Jilin Province, China," Wei (2006) examined forecasting of energy consumption in residential buildings in China. In "Effects of Energy-Saving Measures for Existing Urban Residential Buildings Based on Thermal Simulation and Site Investigation of Energy Consumption," Ouyang (2008) analyzed cooling and heating loads for various climate zones and estimated energy consumption based on the results of thermal simulation.

3. Analysis of Apartment Buildings' Energy Consumption Characteristics

3.1 Changes in Apartment Buildings' Energy Consumption

The changes in apartment buildings in Korea that have increased their energy consumption include the following:

(1) Changes in plans: Unit plans that were only of the corridor type in shape were combined with various stair types and tower types. In particular, balconies were expanded, along with chassis installation, which increased energy consumption.

(2) Modernization of indoor facilities and the use of room cooling: Although living became more convenient because indoor facilities were modernized, thanks to economic development and advances in construction techniques, energy consumption increased drastically. In particular, the use of curtain walls led to increases in room cooling and heating loads. The widespread use of room cooling systems further increased energy consumption in apartment buildings.

(3) Increases in energy consumption with increased construction of high-rise buildings: Greater building heights expose buildings to greater wind velocities, which increase surface heat transfer coefficients, leading to thermal losses. In particular, the structural use of curtain walls necessary for high-rise buildings further increased room heating loads. In addition, the increases in E.V., power, and lighting necessary in the corridors and stairs of high-rise buildings also increased power consumption.

3.2 Simulation Analysis of Shading Conditions with Respect to the Shapes of Apartment Buildings

After identifying differences in energy consumption by households that depend on the shapes of apartment buildings, changes in energy consumption with respect to the height of households and the shapes of housing blocks were examined through simulation analysis. The OpenStudio Sketchup plug-in was used as a shading analysis-modeling tool, and the Autodesk Ecotect Analysis (2011) tool was used for the shading analysis The subjects considered in the shading analysis were apartment buildings located in Seoul divided by type (flat or tower type) and height (medium-low-rise, high-rise, semi-super-high-rise or super-high-rise). Simulation modeling was conducted using the block plans of the subject apartment buildings, arranging each so that the bottom faced south. To conduct a shading analysis of the effects of sunshine at the winter solstice and summer solstice, the effects of sunshine between 10:00 and 16:00 were examined, and complexes of multiple stories facing southeast or southwest were selected (see Table 1.).

Table 1. Shading Analysis Complex Overview

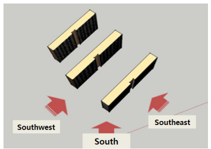
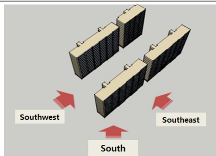
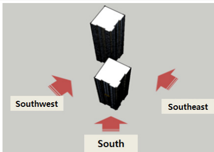
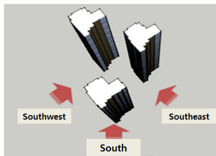
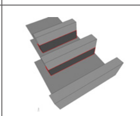
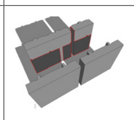
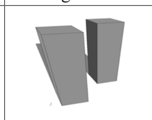
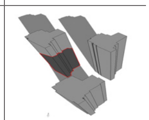
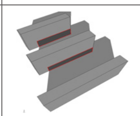
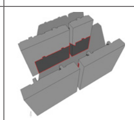
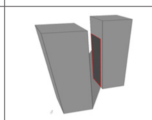
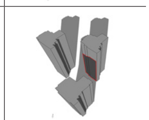
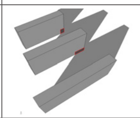
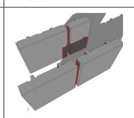
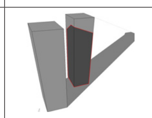
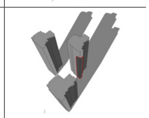
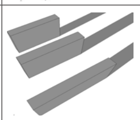
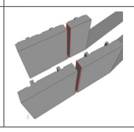
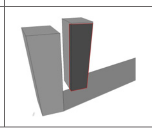
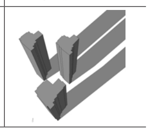
A (Flat, Seoul) complex	B (Flat, Seoul) complex
Medium-high-rise	High-rise
	
C (Tower, Seoul) complex	D (Tower, Seoul) complex
Semi-super-high-rise	Super-high-rise
	

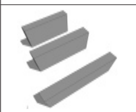
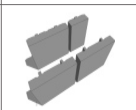
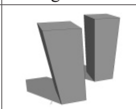
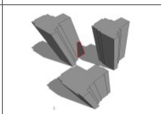
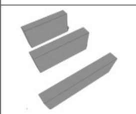
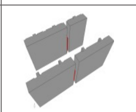
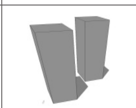
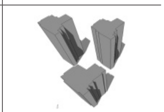
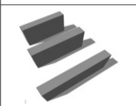
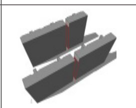
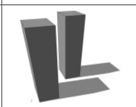
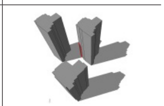
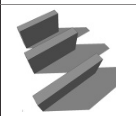
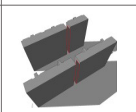
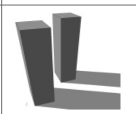
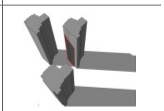
Table 2. Analysis of Shading on the Winter Solstice (Direction: Bottom Facing South)

	Semi-low-rise	High-rise	Semi-super high-rise	Super-high-rise
10 A M				
12 P M				
14 P M				
16 P M				

As Table 2. shows, in the case of flat building types, although there were some lower-floor households with shortages in the amount of sunshine in the morning on the winter solstice due to shading, shading of lower-floor households disappeared in the afternoon. In the case of tower building types, the number of lower-floor households in which shading occurred increased even in the afternoon. These findings indicate that flat-type apartment buildings facing south or southwest are very advantageous in terms of the amount of sunshine received in winter.

As Table 3. shows, during the morning on the summer solstice, few households had shortages in sunshine due to shading, except for some lower-floor households in tower-type complexes. However, in the case of flat-type buildings, shading occurred on the façades of households facing southeast on all floors throughout the afternoon, indicating that these building types are advantageous in terms of minimizing room cooling loads in summer. In the case of tower building types, households facing southwest received direct sunlight, and room cooling loads were increased. Therefore, when housing blocks are arranged to face south, in the case of flat building types, households receive large amounts of sunshine on the winter solstice, while shading prevents exposure to direct sunlight in all households on all floors. However, in the case of tower types, households that face southeast or southwest receive too little sunshine on the winter solstice and too much sunshine on the summer solstice, indicating that tower types are disadvantageous, compared to flat types, in terms of energy consumption.

Table 3. Analysis of Shading on the Summer Solstice
(Direction: Bottom Facing South)

	Semi-low-rise	High-rise	Semi-super high-rise	Super-high-rise
10 A M				
12 P M				
14 P M				
16 P M				

4. Survey of Energy Consumption in Apartment Buildings in their Operational Stage

4.1 Overview

In this study, the energy consumption of apartment buildings in their operational stage was surveyed in 17 complexes constructed in 2000 within the capital area. Actual amounts of energy consumed in one year (Jan. – Dec. 2011) were collected (note that in collecting the values, houses with missing values for some months and those with the highest or the lowest values were excluded). In addition, consistent standards were set, units were converted into kWh, and the amounts of energy consumed were collected separately for household areas, common use areas, month units, and year units. For room heating energy consumption, only city gas consumption was considered, excluding the amounts used for hot water supply and cooking. Electrical energy consumption was calculated to include all use of electricity, such as by home appliances and lighting (see Tables 4. and 5.).

Table 4. Summary of Apartments Surveyed (District Heating)

Item	A	B	C	D	E	F
Completion	'07	'02	'04	'04	'08	'06
Floor Level	12	16	22	22	24	32
Block	3	3	4	4	5	35
Number of Households	216	299	276	212	288	2,678
Average Household Area	145	137	187	182	172	125
Orientation	SE	SE, SW	SE	SE	S	SE, SW
Window Opening Type	Open Window, Available natural ventilation					

Item	G	H	I	J
Completion	'01	'04	'07	'04
Floor Level	32	46	59	69
Block	28	3	1	1
Number of Households	2,178	499	369	480
Average Household Area	147	211	212	223
Orientation	SE, SW	SE, SW	SE, SW	SE, SW
Window Opening Type	Utility room, Open window, Available ventilation			Louvers installed boiler room

Table 5. Summary of Apartments Surveyed (Individual Heating)

Item	K	L	M	N	O	P	Q
Completion	07'	03'	07'	08'	06'	07'	04'
Floor Level	12	15	24	24	32	32	51
Block	3	3	8	6	3	2	1
Number of Households	264	183	275	390	329	280	414
Average area of Household	145	139	146	170	139	134	172
Orientation	SE	SE, SW	SE	SE	S	SE, SW	SE, SW
Opening type of windows	Open Window, Available natural ventilation					Utility room, Open window, Available ventilation	

4.2 Present State of Consumption by Energy Use

The present states of apartment buildings' energy consumption were analyzed by quantifying four types of energy consumption (room heating, electricity, hot water supply, and gas) and calculating their average values per household. The results indicate that energy consumption for room heating is the largest, followed by electricity, hot water supply, and gas, in that order.

Table 6. Energy Consumption by Energy Use

Use	Household Use	Use per unit area (m²)
	kWh/H · yr	kWh/m² · yr
Heating	8,363.28	84.96
Electric	4,129.92	42
Hot Water	3,903.24	40.56
Gas	1,119.6	11.64

4.3 Present State of Energy Consumption by Household Area

To analyze energy consumption by household area, household areas were divided into three categories: 84 m² or less, 84 m² – 120 m², and 120 m² or more. Energy consumption was surveyed for 100 households of each type, for a total of 300 households. Room heating energy and electrical energy accounted for relatively large portions of the energy consumed. The amounts of energy consumed per unit area of households (m²) were also compared and analyzed.

As shown in Table 7., energy (heating and electricity) consumption was found to increase with household area. For both heating and electricity, households larger than 120 m² in area were found to use more energy, by up to 35%, than households smaller than 84 m² in area.

Table 7. Energy Consumption by Household Area

Household Area	Electrical Energy		Heating Energy	
	kWh/H · yr	kWh/m² · yr	kWh/H · yr	kWh/m² · yr
Less than 84 m²	3,567.24	46.68	6,980.92	97.44
84 to 120 m²	4,189.76	41.4	8,622.28	80.88
120 m² or more	5,047.68	34.44	10,325.88	71.04

However, energy consumption per unit area (m²) of households was found to decrease as household area increased. The reason for this was presumed to be the fact that as household areas increase, the areas of non-room heating spaces such as rest rooms, balconies, and dressing rooms also increase.

4.4 Present State of Energy Consumption by Orientation

The directions of the 17 complexes of apartment buildings were surveyed, and the results indicate that 52% of the buildings faced south, 30% of the buildings faced southeast, 9.5% of the buildings faced east, 7.8% of the buildings faced southwest, and 1% of the buildings faced northeast.

Table 8. Energy Consumption by Orientation

Orientation	Electrical Use		Heating Use	
	kWh/H · yr	kWh/m² · yr	kWh/H · yr	kWh/m² · yr
E	4,209.96	3.75	8,544.6	110.16
S	4,123.32	3.34	7,382.88	81.72
SE	4,202.87	3.52	8,043.36	87.6
SW	4,243.32	3.83	7,509.96	85.2
NE	4,426.68	4.28	8,526.72	108.24

As shown in Table 8., room heating and electrical energy consumption was highest in buildings facing east or north and lowest in those facing south or southwest. Energy consumption per unit area (m²) of households was also lowest in buildings facing south. The amounts of energy consumed were concluded to be smaller in buildings facing south because of sunshine.

4.5 Present State of Energy Consumption by Height

To survey the present state of energy consumption by apartment building height, apartment buildings were divided into four groups based on their heights, as shown in Table 9.

Table 9. Analysis of Energy Consumption by Height

Item	Medium-low-rise	High-rise	Semi-super-high-rise	Super-high-rise
Number of Floors	10 – 19	20 – 29	30 – 49	50 or more
Number of Apartments	3	3	2	2
Average Area (m²)	140	171	154	203
Number by Type	Flat 3	Flat 1, Tower 2	Flat 3	Flat 3
Thermal Transmittance	Envelope: 0.47 W/m²·K Window: 1.09 W/m²·K			Low-e Glass: 2.4 W/m²·K

Table 10. Average Monthly Energy Consumption by Height

Number of Floors	Electrical Use		Heating Use	
	kWh/H · yr	kWh/m² · yr	kWh/H · yr	kWh/m² · yr
10–19	7,099.2	69.6	7,503.6	109.2
20–29	9,290.4	86.4	8,864.4	100.8
30–49	10,418.4	93.6	10,040.4	128.4
50 or more	20,125.2	132	11,100	105.6

As shown in Table 10., room heating and electrical energy consumption were highest in super-high-rise apartment buildings (50 stories or more), followed by semi-super-high-rise, high-rise, and medium-low-rise apartment buildings, in that order. In particular, room heating energy consumption in super-high-rise apartment buildings was higher by approximately 68%, and electrical energy consumption was higher by 350%, compared to medium-low-rise apartment buildings. In super-high-rise apartment buildings, room cooling and heating loads are larger because thermal losses are larger, due to the larger outer surfaces, and in particular, the greater loads of transport facilities, power, and ventilation, which drastically increase electricity consumption.

4.6 Present State of Energy Consumption by Apartment Building Type (Flat and Tower Type)

Because apartment buildings of different types differ in terms of ventilation and sunshine time, resulting in large differences in energy consumption, apartment buildings were divided into two types: flat types and tower types. Differences in energy consumption between the two types were analyzed. As shown in Table 12., tower types use more energy for room heating and more electrical energy, by approximately 17% – 20% compared to flat types. In the case of tower-type buildings, most of the outer shells are made of curtain walls, and ventilation is poorer than in flat-type buildings, so energy loads are increased.

Table 11. Survey by Building Type

Block Type	Total%	Average Household Area	Average Number of Floors	Orientation
Flat Type	64%	92 m² – 102 m²	24	South
Tower Type	36%	96 m² – 112 m²	38	

Table 12. Energy Consumption by Type

Household Area	Electrical Use		Heating Use	
	kWh/H · yr	kWh/m² · yr	kWh/H · yr	kWh/m² · yr
Flat Type	4,210.56	41.28	7,210.41	81.52
Tower Type	5,179.1	49.81	8,613.16	97.14

5. Development of Prediction Equations for Apartment Buildings' Energy Consumption

5.1 Overview

To predict apartment buildings' heating energy and electrical energy consumption, prediction equations were developed using multiple regression analysis, using the variables (heat transmission coefficient, area, etc.) considered in domestic environmentally friendly building performance evaluation methods. That is, multiple regression analysis was conducted using the structures' areas and heat transmission coefficient values as independent variables and energy consumption as the dependent variable. Households were classified as "side" households or "center" households, based on their location in their building, and were further classified as belonging to high floors or medium floors, based on differences in areas related to floor heights (see Tables 13. and 14.).

5.2 Results of Room Heating Energy Consumption Regression Analysis

(1) Side households

The results of the regression analysis of heating energy consumption of side households, using seven

Table 13. Input Variable Calculated Values for Side Households

Side	A [m²]	Ks	As	Ko	Ao	Kw	Aw
1	45.88	0.35	17.68	0.45	17.89	2.16	11.53
2	45.88	0.35	17.71	0.45	16.1	2.17	13.23
3	39.56	0.35	20.37	0.45	12.63	2.17	10.44
4	48.92	0.35	18.19	0.45	16.44	2.17	13.45
5	48.92	0.35	18.43	0.45	18.24	2.17	11.65
6	59.64	0.35	18.44	0.45	32.19	2.17	20.54
7	44.32	0.35	15.57	0.45	19.49	2.17	11.89
8	44.32	0.35	15.75	0.45	19.49	2.17	11.89
9	44.32	0.35	15.57	0.45	19.49	2.17	11.89
10	48.92	0.35	18.43	0.45	18.41	2.16	11.65
11	39.56	0.35	20.37	0.45	13.89	2.16	9.18
12	59.64	0.35	18.44	0.45	32.19	2.17	20.54
13	48.92	0.35	18.43	0.45	18.24	2.17	11.65
14	45.88	0.35	17.53	0.45	17.68	2.16	11.46
15	45.88	0.35	17.56	0.45	15.91	2.17	13.23
16	39.56	0.35	20.19	0.45	12.50	2.17	10.35
17	48.92	0.35	18.30	0.45	16.25	2.17	13.35
18	48.92	0.35	18.27	0.45	18.03	2.17	11.58
19	59.64	0.35	18.28	0.45	31.86	2.17	20.40
20	44.32	0.35	15.23	0.45	18.95	2.17	11.67

* Ks: side wall heat transmission coefficient; Ko: outer wall heat transmission coefficient; Kw: window heat transmission coefficient;
Kd: front door heat transmission coefficient;
Kr: roof heat transmission coefficient;
Kf: floor heat transmission coefficient; As: side wall area;
Ao: outer wall area; Aw: window area; A: exclusive use area;
Ad: front door area; Af: floor area; Ar: roof area.

Table 14. Input Variable Calculated Values for Center Households

Center	A [m²]	Ko	Ao	Kw	Aw
1	45.88	0.45	26.05	2.16	9.70
2	45.88	0.45	27.31	2.16	9.70
3	39.56	0.45	22.71	2.16	7.88
4	47.40	0.45	28.8	2.16	9.76
5	47.09	0.45	26.28	2.16	9.75
6	59.64	0.45	31.73	2.17	20.45
7	39.59	0.45	18.61	2.16	7.91
8	39.59	0.45	18.61	2.16	7.91
9	39.59	0.45	18.61	2.16	7.91
10	49.53	0.45	27.78	2.16	9.85
11	39.56	0.45	21.55	2.16	7.88
12	59.64	0.45	31.73	2.17	20.45
13	47.09	0.45	26.28	2.16	9.75
14	45.88	0.45	17.75	2.16	11.48
15	45.88	0.45	15.97	2.17	13.23
16	39.56	0.45	12.54	2.17	10.38
17	48.92	0.45	16.32	2.17	13.38
18	48.92	0.45	18.10	2.17	11.60
19	59.64	0.45	31.97	2.17	20.45
20	44.32	0.45	19.13	2.17	11.76

inputs as independent variables and room heating energy consumption as the dependent variable, are shown in Table 15.

Table 15. Multiple Regression Analysis Results for Heating Energy Use for Side Households (Model Summary)

R	R^2	Modified R^2	Standard error of the estimate
0.917	0.841	0.780	1.37119

a. Predicted: (Constant), Aw, As, Ko, Kw, A, Ao, Ks

The R^2 (coefficient of determination) of the multiple regression equation obtained for the side households was found to be 0.841, indicating a strong relationship between the independent variables and the dependent variable. The multiple regression equation obtained for heating energy use for side households is shown as Formula 1.

$$Y = 1736.741 - 1.499X_1 - 6957.623X_2 + 7.269X_3 + 1767.372X_4 + 0.365X_5 - 90.892X_6 + 4.295X_7 \quad \text{(Formula 1)}$$

Y: predicted side household room heating energy consumption (GJ)
X_1: exclusive use area (m²),
X_2: side wall heat transmission coefficient, X_3: side wall area (m²)
X_4: outer wall heat transmission coefficient, X_5: outer wall area (m²),
X_6: window heat transmission coefficient, X_7: window area (m²)

The room heating energy consumption of side households of apartment buildings can be predicted using this regression equation. A comparison of predicted and actual room heating energy consumption values for side households is shown in Fig.1.

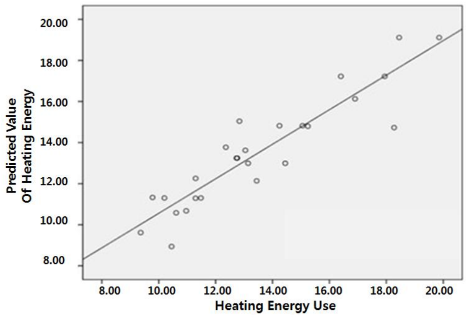


Fig.1. Predicted Versus Actual Heating Energy Use for Side Households

(2) Center households

The results of the regression analysis of heating energy consumption for center households, using five inputs as independent variables and room heating energy consumption as the dependent variable, are shown in Table 16.

Table 16. Multiple Regression Analysis Results for Heating Energy Use for Center Households (Model Summary)

R	R^2	Modified R^2	Standard error of the estimate
0.876	0.767	0.709	1.2407

a. Predicted: (Constant), Aw, As, Ko, Kw, A, Ao, Ks

The R^2 of the regression was found to be 0.767, indicating a strong relationship between the independent variables and the dependent variable. The multiple regression equation obtained for heating energy use for center households is shown as Formula 2.

$$Y = -287.832 + 0.218X_1 - 1069.311X_2 - 0.019X_3 + 360.230X_4 + 0.455X_5 \quad \text{(Formula 2)}$$

Y: predicted center household room heating energy consumption (GJ),
X_1: exclusive use area (m²),
X_2: outer wall heat transmission coefficient, X_3: outer wall area (m²),
X_4: window heat transmission coefficient, X_5: window area (m²)

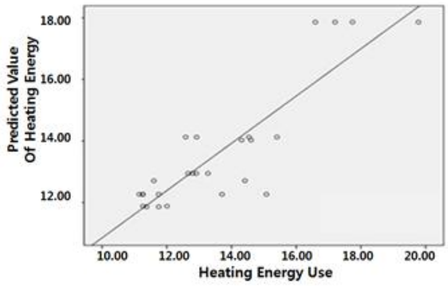


Fig.2. Predicted Versus Actual Heating Energy Use for Center Households

A comparison of predicted and actual room heating energy consumption values for center households is shown in Fig.2.

5.3 Results of Electrical Energy Consumption Regression Analysis

(1) Side households

The results of the regression analysis of electrical energy consumption for side households, using seven inputs as independent variables and electrical energy consumption as the dependent variable are shown in Table 17.

Table 17. Multiple Regression Analysis Results for Electrical Energy Use for Side Households (Model Summary)

R	R^2	Modified R^2	Standard error of the estimate
0.961	0.924	0.817	0.17954

a. Predicted: (Constant), Aw, As, Ko, Kw, A, Ao, Ks

The R^2 of the regression was found to be 0.924, indicating a strong relationship between the independent variables and the dependent variable. The multiple regression equation obtained for electrical energy use for side households is shown as Formula 3.

$$Y = -214.023 + 0.376X_1 + 973.901X_2 - 1.169X_3 - 499.919X_4 + 0.008X_5 + 52.325X_6 - 0.836X_7 \quad \text{(Formula 3)}$$

Y: predicted side household electrical energy consumption (MWh)
X_1: exclusive use area (m²),
X_2: side wall heat transmission coefficient, X_3: side wall area (m²),
X_4: outer wall heat transmission coefficient, X_5: outer wall area (m²),
X_6: window heat transmission coefficient, X_7: window area (m²)

A comparison of the predicted and actual electrical energy consumption values for side households is shown in Fig.3.

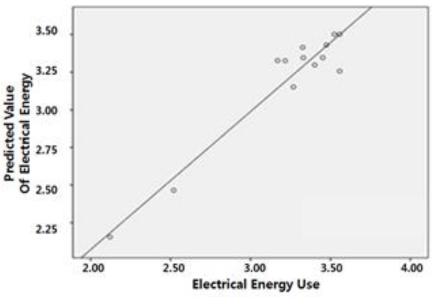


Fig.3. Predicted Versus Actual Electrical Energy Use for Side Households

(2) Center households

The results of the regression analysis of electrical energy consumption for center households, using five inputs as independent variables and electrical energy consumption as the dependent variable, are shown in Table 18.

Table 18. Multiple Regression Analysis Results for Electrical Energy Use for Center Households (Model Summary)

R	R^2	Modified R^2	Standard error of the estimate
0.932	0.869	0.775	0.19851

a. Predicted: (Constant), Aw, As, Ko, Kw, A, Ao, Ks

The R^2 of the regression was shown to be 0.869, indicating a strong relationship between the independent variables and the dependent variable. The multiple regression equation obtained for electrical energy use for center households is shown as Formula 4.

$$Y = 198.828 + 0.116X_1 + 65.301X_2 - 0.002X_3 - 107.036X_4 + 0.027X_5 \quad \text{(Formula 4)}$$

Y: predicted center household electrical energy consumption (MWh)
X_1: exclusive use area (m²),
X_2: outer wall heat transmission coefficient,
X_3: outer wall area (m²),
X_4: window heat transmission coefficient, X_5: window area (m²)

A comparison of the predicted and actual electrical energy consumption values is shown in Fig.4.

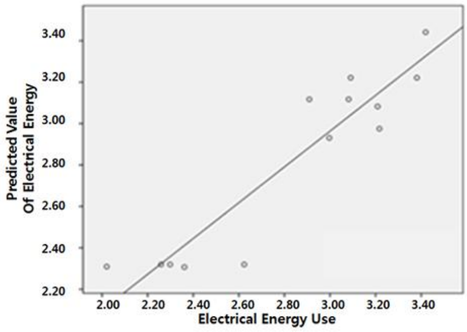


Fig.4. Predicted Versus Actual Electrical Energy Use for Center Households

5.4 Evaluation of the Explanatory Power of the Prediction Equations Developed

(1) Check of the level of multicollinearity

Multicollinearity refers to the relationships between variables considered in multiple regression analysis when there are three or more variables. Even if an independent variable has high explanatory power for the dependent variable, the explanatory power will be lower if multicollinearity among the independent variables is high. Multicollinearity can be checked through the tolerance limit and variance inflation factor (VIF) among indicators. These two indicators inform the degree to which one independent variable is explained by all other independent variables.

In this study, multicollinearity among the independent variables was checked to assess the effect it might have on the regression results. A tolerance limit of 0.1 or higher was used, and the variance inflation factor was shown to be 10 or lower, indicating that multicollinearity was not an obstacle to obtaining meaningful regression equations. The results of the check of multicollinearity are shown in Tables 19. and 20.

Table 19. Review of Multicollinearity of the Independent Variables for Center Households

H	SP	Collinearity		E	SP	Collinearity	
Model		TV	VIF	Model		TV	VIF
(C)	0.000			(C)	0.035		
Af	0.000	0.103	7.715	Af	0.001	0.180	9.558
Ko	0.000	0.303	3.295	Ko	0.053	0.287	3.480
Ao	0.000	0.192	8.880	Ao	0.064	0.188	8.331
Kw	0.000	0.243	6.975	Kw	0.159	0.197	7.277
Ka	0.000	0.160	8.660	Ka	0.004	0.158	6.202

* H: heating; SP: significance probability; TV: tolerance value;
Af: floor area; Ks: side wall heat transmission coefficient;
Ko: outer wall heat transmission coefficient;
Kw: window heat transmission coefficient; Aw: window area;
Kf: floor heat transmission coefficient; As: side wall area;
Ao: outer wall area; A: exclusive use area

Table 20. Review of Multicollinearity of the Independent Variables for Side Households

H	SP	Collinearity		E	SP	Collinearity	
Model		TV	VIF	Model		TV	VIF
(C)	0.000			(C)	0.056		
Af	0.000	0.113	7.321	Af	0.008	0.105	9.812
Ks	0.000	0.108	11.865	Ks	0.024	0.113	8.523
As	0.000	0.113	9.212	As	0.020	0.106	9.634
Ko	0.000	0.165	8.446	Ko	0.011	0.232	3.892
Ao	0.000	0.107	8.653	Ao	0.064	0.102	8.711
Kw	0.000	0.434	2.302	Kw	0.020	0.126	7.936
Ka	0.000	0.203	9.154	Ka	0.001	0.101	9.012

Table 21. R-squared Values of Prediction Equations for Energy Consumption

H·E Use Prediction Formula		E·E Use Prediction Formula	
Side Households	Center Households	Side Households	Center Households
$R^2 = 0.841$	$R^2 = 0.767$	$R^2 = 0.924$	$R^2 = 0.869$

(2) Review of the explanatory power of the regression equations developed

The coefficients of determination of the regression equations developed are shown in Table 21.

R^2 (R-squared) is the coefficient of determination, which indicates the percentage of the variance of a dependent variable that is explained by an independent variable. The value of R^2 is between 0 and 1.

The total sum of squares (Total SS) represents the entire variance in cases where dependent variables are estimated by average values. The regression sum of squares (SSR) represents the portion of the variance that is explained when dependent variables are estimated using regression equations. The residual sum of squares (SSE) represents the portion of the variance that is not explained when dependent variables are estimated using regression equations. Therefore, R^2 can be expressed as the ratio of the variance of a dependent variable that is explained by independent variables to the entire variance of the dependent variable, as shown in Formula 5.

$$R^2 = \frac{SSR}{Total\,SS} \quad \text{(Formula 5)}$$

Chapter 19, "Energy Estimating and Modeling Methods," of the 2009 edition of the ASHRAE Fundamentals Handbook (SI) describes the coefficient of determination R^2 as a statistical measure of the goodness of fit of a regression model, and states that "for the purposes of tuning for a performance contract, as a rule of thumb the value of R^2 should never be less than 0.75."

Thus, the coefficients of determination of the regression equations developed in this study satisfy the criterion stated in the 2009 ASHRAE Fundamentals Handbook (SI) Edition.

6. Conclusions

The results of this study are summarized as follows:

(1) In recently constructed apartment buildings in Seoul, unit plan shapes that were previously only corridor types have had stair types and tower types added and balconies have been expanded, along with chassis installation, which have increased energy consumption. In addition, modernization of indoor facilities that has resulted from economic development and advances in construction techniques, as well as the use of room cooling systems and the use of curtain walls, E.V., and powered machines necessary in high-rise buildings have all increased energy consumption in apartment buildings.

(2) The results of shading simulations for different types of apartment buildings (flat and tower types) and different heights (medium-low-rise, high-rise, semi-super high-rise, and super-high-rise) showed that for all households on all floors of flat building types facing south or southwest were advantageous in obtaining sunshine in winter and had lower room cooling loads because of shading from direct sunlight. However, tower-type apartment buildings were shown to receive too little sunshine in winter and too much sunshine in summer, compared to flat types, thus requiring larger amounts of energy for heating and cooling, respectively. To be more specific, in the case of flat building types, although there were some households with a shortage in the amount of sunshine received due to shading of lower-floor households in the complexes in the morning, in the afternoon, shading of lower-floor households in flat-type buildings disappeared. In contrast, in the case of tower-type buildings, the number of lower-floor households in which shading occurred increased even in the afternoon.

(3) The results of surveys of actual states of energy consumption in apartment buildings in their operational stage in 17 complexes of apartment buildings located in Seoul and the capital area over the course of one year showed that room heating energy accounted for the largest share of the average household energy consumption, followed by electricity, hot water supply, and gas, in that order. Room heating energy consumption was highest in the winter and decreased to 50% during intermediate periods and to almost zero in the summer. Electrical energy consumption was highest in July and August and was similar during the remaining months of the year, without any large variation. Hot water supply energy consumption was highest in the winter, was steady in intermediate periods, and was approximately 50% of the winter level in the summer. Gas consumption was highest in January, February, and March and was consistently lower in the remaining months of the year. Both room heating energy consumption and electrical energy consumption increased with household area (84 m^2 or smaller, 84 m^2 – 120 m^2, 120 m^2 or larger). Households greater than 120 m^2 in size used up to 35% more energy than households smaller than 84 m^2 in size. However, energy consumption per unit area (m^2) decreased as household area increased. The reason for this was presumed to be that as household areas increase, the areas of non-room heating spaces, such as rest rooms, balconies, and dressing rooms, also increase. Households facing east or northeast showed the highest energy consumption (both room heating and electrical), and those facing south or southwest showed the lowest consumption. In particular, consumption per unit area (m^2) was shown to be the lowest in households

facing south, suggesting that smaller amounts of energy are consumed in households facing south because of sunshine. Super-high-rise apartment buildings (50 stories or higher) showed the highest energy consumption (both room heating and electrical) followed by semi-super-high-rise, high-rise, and medium-low-rise apartment buildings, in that order. In particular, room heating energy consumption in super-high-rise apartment buildings was shown to be approximately 68% higher, and electrical energy consumption was shown to be approximately 350% higher, compared to medium-low-rise apartment buildings. These findings suggest that in super-high-rise apartment buildings, room cooling and heating loads are larger because of larger thermal losses associated with the larger outer surfaces, and in particular, the greater loads of transport facilities, power, and ventilation, which drastically increase electricity consumption. Tower-type buildings were found to use approximately 17% – 20% more energy than flat types. In the case of tower-type buildings, most outer shells are made of curtain walls, and ventilation is poorer than in flat-type buildings, so energy loads are increased.

(4) Prediction equations for heating energy consumption and electrical energy consumption for apartment buildings in their operational stage were developed by conducting multiple regression analyses using the areas of structures and heat transmission coefficient values as independent variables and energy consumption parameters as dependent variables. The goodness of fit of the regression equations was assessed in terms of the R^2 values of the regressions, which were 84.1% for room heating energy consumption for side households, 76.7% for room heating energy consumption for center households, 92.4% for electrical energy consumption for side households, and 86.9% for electrical energy consumption for center households. These R^2 values satisfy the criterion of R^2 greater than 75% stated in the 2009 ASHRAE Fundamentals Handbook (SI) Edition.

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