Impact of Urban and Building Form and Microclimate on the Energy Consumption of Buildings
- Based on Statistical Analysis-

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Abstract
This study investigates certain correlations between the impacts of urban and building form and microclimate on the energy consumption of buildings. It applies microscopic elements such as urban form and tissue, building form and character, and microclimate as factors in the energy consumption of buildings. To this end, the energy consumption of selected buildings in Seoul in August of 2014 was analyzed. Based on microscopic elements within a radius of 500 meters of 23 Automated Weather Station (AWS) measurement points selected by the Meteorological Office of the City of Seoul, the study employed both ordinary least square (OLS) and gamma regression, techniques that have been widely applied in this field of study. The analysis results show that compared to OLS, gamma regression is more suitable for analyzing the energy consumption of buildings. With the exception of a few elements, the urban form and character elements demonstrate a significant relation to the energy consumption of buildings. It is also found that microclimate elements such as wind speed and humidity are pertinent to the energy consumption of buildings. This study is expected to contribute to the foundation for the formation of sustainable and resilient cities through the reduction of energy consumption.

Keywords: urban design; OLS (Ordinary Least Square); gamma regression; building energy consumption; urban form and urban tissue; building form and building character; microclimate

1. Introduction
Energy has long played a significant role in human history. The discovery of or a change to new forms of energy has been an indispensable factor in human development; ownership of energy resources creates an enormous impact on our efforts to overcome the threats, obstacles, and limitations posed by nature. This relation between humans and energy remains in effect today. However, since the 1970s we have been beginning to recognize the limits of energy and started to change our ways of behavior.

Since the emergence of Environmentally Sound and Sustainable Development (ESSD) in the 1970s, efforts to acknowledge the limits of energy and brace for the resultant threats have been carried out in various fields. The urban planning and architecture area is no exception. A wide range of endeavors from seeking urban forms with lower energy needs to the development of architectural models with low energy usage and technologies for saving energy have been pursued. Against this backdrop, this study is aimed at analyzing the impact of urban and building elements on the energy consumption of buildings, thereby revealing ways to further reduce the energy consumption of buildings.

2. Literature Review
2.1 Literature Review
This study focuses on the microclimates of buildings since they are affected by urban form and tissue and the layout of buildings and, in turn, influence the energy consumption of buildings.

Studies related to this issue can be divided into two categories. First, research has been reported that analyzed the relation between urban form and tissue and microclimate. Baruch Givoni (1998) found that wind speed in areas with high density and high-rise buildings was slower than in other areas, and also proved that the size and density of cities affected temperatures within the city. He also discovered in a study on Seville in 1998 that the depth of roads influenced the temperature of the city. Gideon S. Golany (1996) concluded that a grid network of streets promotes the circulation of air to the innermost part
of the city. Ingegärd Eliasson (1994) investigated the impact of urban form on temperatures through a three-year study on Göteborg in Sweden. A study on Athens carried out by Mat Santamouris and P. Littlefair (1998) showed that temperatures are governed by the flow of air rather than by the direction of an urban canyon and that shade on the road surface is maximized when a road runs north-south. Gerald Mills (1997) studied the impacts of building shape and the distance between buildings on exposure to sunlight and on light factors. Yasushi Sakakibara (1996) found out through model simulation that a higher proportion of the dimensions of roads to the height of walls of adjacent buildings leads to a greater thermal storage effect. Roger G. Barry and Richard J. Chorley (2009) proposed that high thermal capacity and various materials and building shapes within cites alter the flow of air, thereby forming a canyon in the passage of air. Arthur H. Rosenfeld et al. (1998) analyzed in their study on the Los Angeles basin the relation between the change in the colors of roofs and ceilings and an increase in albedo and revealed the awning effect of roadside trees and trees planted for shade. Focusing on the relation between urban form, building form and microclimate, Dana Raydan and Koen Steemers (2006) proposed the concept of Environmental Urban Design.

Second, research has been published that investigated the direct relation of ground surface temperature, urban and building surface temperature and the energy consumption of buildings. J.R. Simpson and E.G. McPherson (1997) analyzed the impacts of types of roofing materials on ground surface temperature and the energy consumption of buildings in a study implemented in the summer of 1990. Danny S. Parker and Stephen F. Barkaszi Jr. (1997) analyzed the impact of a change in albedo on the energy consumption of nine residential buildings in Florida between 1991 and 1994, and found that albedo did indeed affect the reduction of the energy consumption of buildings.

The above studies are meaningful since, unlike previous research, they illuminate the significance of microscopic space, despite having the following four limitations.

First, they failed to generalize any theory since, due to the lack of statistical data or investigation of a small number of sites, they relied on observational studies.

Second, some of them applied inappropriate statistical or research techniques. Statistical analysis is a useful tool for eliciting generalized outcomes. However, if applied unsuitably it can lead to an inadequate conclusion. In particular, these studies often applied general OLS without considering the dependent variable of the energy consumption of buildings.

Third, research was carried out using controllable data rather than searching for a comprehensive model dealing with the relations between urban form and tissue, building shape and character, microclimate, and the energy consumption of buildings. In this regard, the third limit is related to the first.

Fourth, they failed to consider urban form and tissue as elements affecting the energy consumption of buildings. They regard these factors to influence only microclimate. However, J.R. Simpson and E.G. McPherson (1997) saw microclimate, notably surface temperature, as an element affecting the energy consumption of buildings. In addition, according to the study by Ingegärd Eliasson (1994), microclimate is affected by urban form and tissue. Therefore, the direct and indirect impacts of urban form and tissue on the energy consumption of buildings should be investigated, despite being ignored in previous research.

This study seeks to establish a comprehensive model by complementing the limits found in existing research and applying a wide range of statistical data while utilizing a more accurate statistical method.

2.2 Issues and Hypotheses

Based on the limits of previous research, this study suggests the following issues:

First, OLS, which has been broadly utilized, is not a suitable method for the analysis of the energy consumption of buildings.

Second, urban form and tissue, which have not been subjected to attention in existing research, are elements affecting the energy consumption of buildings.

Third, not only surface temperature, as in the focus of previous research, but also microclimate factors such as wind speed and humidity influence the energy consumption of buildings.

The hypotheses to be proposed in this study on the basis of the issues above are as follows:

1. The gamma regression model has more explanatory power than does OLS in analyzing the energy consumption of buildings. OLS is not an appropriate model for the analysis of the energy consumption of buildings.

2. Urban form and tissue have a meaningful relation to the energy consumption of buildings.

3. Microclimate factors such as temperature, wind speed, and humidity have a meaningful relation to the energy consumption of buildings.

3. Analysis Structure

3.1 Analysis Model: Gamma Regression

Gamma regression is a generalized linear model (GLM) that can be used when the normality of a dependent variable is not fulfilled. The generalized linear model is a statistical model that excludes the ordinary linear model's assumptions of a normal distribution of reference variables and equivalence of distribution and is based on an assumption of independence of data and additivity of the model. By not being bound by these assumptions, it allows the use of extensive abnormal distribution data. A GLM is
a flexible generalization of ordinary linear regression allowing the estimation of parameters by satisfying the linearity and additivity of a model via a link function, even when the relation of reference variables and predicted variables is linear or nonlinear.

While ordinary linear regression relies on the direct relation of observed data on reference variables and predicted variables, GLM focuses on the fact that the relation of the parameters of reference variables (i.e. theoretical average) and predicted variables is linear. In other words, in the case of regression analysis, \( E(Y|X) = X\beta \). Therefore, when the relation of reference variables and predicted variables is nonlinear (i.e. logistic and probit models) and multiplicative (i.e. log linear model) rather than additive, the linear relation is secured using a link function and the value of the link function \( g(.) = \eta \) is used as a reference variable.

The value of a link function is drawn from the function of the parameters of reference variables following the assumption that observed data \( Y \) is equal to the value of a link function.

An analysis model used in this study is based on the pattern theory that the value of a link function is identical through all the data, even though it could be different from observed data at the individual level. An ordinary linear model is a unique form of generalized liner model in which a link function is an identity function \( \eta = Y \).

As for gamma distribution and gamma distribution function, which would be used as a link function, a gamma model is applicable only when a response variable is zero or greater. Generally used when a response variable is a link variable, it is also available in count variables with a wide range of values.

\[
f_y(y; \mu, \phi) = \frac{1}{y^{1/\phi} \mu^{\phi/\phi}} \exp \left( -\frac{y}{\mu} \right) \cdots (1)
\]

The above equation can be transposed into the following exponential function:

\[
f_y(y; \mu, \phi) = \exp \left[ \frac{y/\mu - (\ln \mu)}{\phi} - \frac{1-\phi}{\phi} \ln y - \ln \phi - \ln F \left( \frac{1}{\phi} \right) \right]
\]

3.2 Variables Analyzed

The following variables were applied for the verification of the above hypotheses.

First, variables related to urban form and tissue that had been proved in existing research (Baruch Givoni, 1998; Gideon S. Golany, 1996; Mat Santamouris & Littlefair P., 1998) to influence microclimates were employed. This study chose these variables under the assumption that they will directly affect the energy consumption of buildings. The directional orientation of buildings, distance between buildings, width of public space in front of buildings, and width and shade of roadside trees are some examples.

Second, variables related to building form that have been revealed in previous research (J.R. Simpson, & E.G. McPherson, 1997; Danny S. Parker, & Stephen F. Barkaszi Jr., 1997) to affect the energy consumption of buildings, were applied. The shape of the building plan, color and shape of the roof, shape of lower levels, materials and color of the façade, window area, usage, and structure are all examples.

Lastly, not only wind speed, temperature, humidity, and the ambient temperature of buildings, but also gradient and amount of solar radiation were introduced as variables related to microclimate.

In addition, the study utilizes the projected lifespan of a building, gross area, and height of buildings, which are known to be relevant to the energy consumption of buildings, as control variables. It also employs façade area, ratio of S to V, ratio of W to D, and ratio of S to F as thermal transmission variables. Tables 2. to 4. show the operational definition of each variable.

3.3 Analysis Target and Data

This study utilizes data on 22,439 buildings within a radius of 500 meters (0.79km²) of 23 AWS measurement points chosen by the Meteorological Office of the City of Seoul. It applied the radius of 500 meters because studies by Wilmers (1991) and Yunnam et al. (2015) show that temperatures are maintained similarly within such a boundary. The target areas are shown in Fig.1. below.

![Fig.1. Target Areas within a 500-meter Radius of (0.79km²) of 23 AWS Measurement Points](image)

Official data related to the variables of the target areas was obtained from the Seoul Metropolitan Government. As for the energy consumption of the buildings, a dependent variable, data collected and published by the Ministry of Land, Infrastructure and Transport in 2013 were used.

Administrative information on buildings managed by the Ministry of Land, Infrastructure and Transport, and microclimate data from AWS measurement points provided by the Korean Meteorological Administration were utilized. For the ambient temperature of buildings, Landsat 8 satellite image data for the central portion of the Korean Peninsula provided by United...
States Geological Survey (USGC) were converted into thermal imagery. ENVI 5.3 was employed in the process and the temperatures of target buildings were extracted from the data using GIS.

Data on the orientation and gradient of buildings and distance between roadside trees were created by analyzing the Urban Planning Information System (UPIS) data provided by the Seoul Metropolitan Government with ArcGIS. ArcGIS 10.3 was utilized in all the analysis using GIS.

The data for the descriptive statistics of each variable are shown in Tables 1. and 2. below.

### 4. Analysis Results

#### 4.1 OLS versus Gamma Regression

A histogram of the energy consumption of buildings, the dependent variable of this study, is shown in Fig.2. The value is greater than zero and concentrated on low figures with a long tail.

Skewness and kurtosis tests were also carried out with the result of 3.14 and 4.39, respectively (greater than 2), which means it is not a normal distribution. To allow a stricter analysis, a Shapiro-Wilk test was carried out as well. The $p$-value of the result was 0.03 (greater than 0.05), which dismisses the null hypothesis. Therefore, it did not present a normal distribution.

As a result of these tests, it was confirmed that the dependent variables for the study do not show a normal distribution. Under this condition, OLS is not appropriate for analysis.

For a clear comparison of OLS and gamma regression results, the Akaike Information Criterion (AIC) of these two models were compared. The figures were 89.2153 and 17.9972, respectively, which can lead to the conclusion that gamma regression is a more suitable technique for the analysis of the data in the study.

However, normality test results of the dependent variables indicate that they do not show a normal distribution and that the histogram is skewed to the left.
with a long tail on the right. Therefore, it is premature to suppose that they present a gamma distribution and apply gamma regression, since based on the histogram of dependent variables as seen in Fig.2., it is necessary to check first whether they follow a log-normal distribution. If the dependent variables present a log-normal distribution, then OLS regression for logarithmic dependent variables would be more appropriate than gamma regression. To check this, this study applied OLS regression before employing gamma regression. The histogram is shown in Fig.3.

![Histogram of Logarithmic Energy Consumption of Buildings](image)

Fig.3. Histogram of Logarithmic Energy Consumption of Buildings

This histogram is skewed to the right, the skewness value seems out of normality, and the kurtosis appears similar to a normal distribution. Skewness and kurtosis tests were carried out for the quantitative analysis with a result of -0.340 and 2.892, respectively (greater than 2), which means it is not a normal distribution even though it was mitigated compared to before logarithmic dependent variables were applied.

A Shapiro-Wilk test was carried out for the further determination of a normal distribution. The $p$-value of the result was smaller than 0.01 (greater than 0.05), which means it did not present a normal distribution. To allow stricter analysis, a Shapiro-Francia test was carried out as well. The $p$-value of the result was smaller than 0.01 (greater than 0.05), which indicates that it did not present a normal distribution.

These analysis results show that gamma regression, not OLS or OLS for logarithmic dependent variables, is the most suitable technique for the analysis of the dependent variables in this study.

### 4.2 Analysis of Results

The results of the analysis of the variables that show significance are as follows.

First, the relations of the urban form and tissue variables and the energy consumption of buildings were examined. The results indicate that the energy consumption of buildings facing south or southwest decreases compared to that of buildings facing north, while the energy consumption of buildings facing northwest increases. This can be explained by the fact that buildings facing west experience light incidence for a longer period of time. For the aspect of the width of public space in front of buildings, it is determined that greater width results in higher energy consumption. An increase in the amount of solar radiation may be the cause, but further study is required. Meanwhile, both the presence of shade from roadside trees and distance between roadside trees reduce the energy consumption of buildings. However, the degree of the impact is not great.

Second, the relations between building form variables and the energy consumption of buildings were examined. Buildings with a square plan show lower energy consumption than do those with a triangular or circular plan. Meanwhile, both greater width and depth of buildings result in higher energy consumption. However, there are different views on the optimum ratio of width and depth of buildings, and hence a need for further study. As for roof shape, it is found that buildings with flat roofs consume more energy than do those with gabled roofs. Most roof colors reduce energy consumption compared to gray. In particular, buildings with red roofs consume significantly lower energy, which is the result of albedo differing depending on color. A greater setback distance for the ground floor leads to lower energy consumption, while the existence of pilotis reduces the energy consumption of buildings. It is judged that pilotis block solar radiation during summer, thereby creating a path for wind, although further study is needed to determine the exact cause of this phenomenon. As for façade materials, rock, brick, and steel reduce the energy consumption of buildings, but glass and wood increase it. Buildings with blue façades consume less energy compared to those with achromatic tones, while a greater proportion of window area raises energy consumption. As for the usage of buildings, it is found that apartment and cultural and religious buildings consume less energy than do single family homes, while neighborhood commercial buildings and retail and entertainment buildings expend more energy.

Third, the relations of microclimate and surrounding natural environment variables and the energy consumption of buildings were examined. Higher wind speeds result in less energy consumption, while higher temperature and humidity lead to greater energy consumption.

The ambient temperature of buildings has a huge impact on increasing energy consumption. Also, gradient and amount of solar radiation show a meaningful relation with the energy consumption of buildings.

Fourth, the relations of control variables and amount of energy consumption were not different from the facts as already established. Higher projected lifespan of a building and gross area result in greater energy consumption; higher façade area, S/V ratio, and S/F ratio lead to greater energy consumption as well.
Table 3. OLS versus Gamma Regression

| Section                          | Variable                                             | OLS Model             | Gamma Regression Model |
|----------------------------------|------------------------------------------------------|-----------------------|-----------------------|
|                                  |                                                      | Coeff. | S.E   | Coeff. | S.E   |
| Orientation (Standard: North)    |                                                      |         |       |         |        |
| Orientation                      | Northeast                                            | 132.2255 | 229.6596 | -0.0166 | 0.0453 |
|                                  | East                                                 | 212.7751 | 203.7239 | -0.0061 | 0.0399 |
|                                  | Southeast                                            | 389.7877 | 246.3616 | 0.0067  | 0.0485 |
|                                  | South                                                | -162.4439 | 190.3613 | -0.0765* | 0.0373 |
|                                  | Southwest                                             | 218.9508 | 223.1786 | -0.0724† | 0.1560 |
|                                  | West                                                 | 283.9325 | 202.0662 | -0.0202 | 0.0394 |
|                                  | Northwest                                             | 798.835** | 246.8331 | 0.1392** | 0.0487 |
| Urban Form and Tissue            | Distance between Buildings                             | 1.5044 | 1.3506 | 0.0013 | 0.0057 |
|                                  | Width of Public Space in front of Buildings           | 28.2783 | 28.3314 | 0.0005† | 0.0002 |
|                                  | Presence of Shade from Roadside Trees                 | -846.0765 | 537.1154 | -0.1499 | 0.1079 |
|                                  | Distance between Roadside Trees                       | 96.8175 | 84.5343 | -0.0077 | 0.0172 |
|                                  | Existence of Diagonal Shapes                          | -149.9003 | 660.0835 | 0.1392** | 0.0487 |
| Shape of Plan                    | Existence of Square Shapes                            | -170.1167 | 594.6048 | -0.4411** | 0.1161 |
|                                  | Width of Buildings                                    | 106.653** | 18.3117 | 0.0175** | 0.0037 |
|                                  | Depth of Buildings                                    | 69.6645** | 19.7752 | 0.0114** | 0.0041 |
| Shape of Roof                    | Existence of Flat Roof                               | 119.9568 | 190.5264 | 0.0897** | 0.0376 |
| Color of Roof (Standard: gray)   | Green                                                | -45.4544 | 121.3571 | 0.0013 | 0.0238 |
|                                  | Blue                                                  | -178.5446 | 288.9202 | 0.0005† | 0.0566 |
|                                  | Red                                                   | -481.2789* | 222.3189 | -0.0724† | 0.1292 |
| Shape of Lower Level             | Height of Ground Floor                                | -99.5326 | 106.6661 | -0.0171 | 0.0212 |
|                                  | Setback Distance of Ground Floor                      | -78.8185** | 39.3675 | -0.0241‡ | 0.0074 |
|                                  | Existence of Piloti                                   | -1080.172** | 357.1947 | -0.3097** | 0.1357 |
| Façade Material (Standard: concrete) | Rock                                                | -250.6006 | 260.8799 | -0.1309** | 0.0510 |
|                                  | Brick                                                 | -530.654† | 276.2274 | -0.1368** | 0.0527 |
|                                  | Tile                                                  | 62.9079 | 341.0311 | 0.0193 | 0.0665 |
|                                  | Steel                                                 | -253.7101 | 1171.642 | -0.5444* | 0.2292 |
|                                  | Wood                                                  | 1444.327* | 698.9507 | 0.3101** | 0.1368 |
|                                  | Glass                                                 | -1790.886** | 695.0558 | 0.5625** | 0.1357 |
| Color of Facade (Standard: Achromatic) | Green                                              | 179.5 | 279.1967 | 0.0083 | 0.0551 |
|                                  | Blue                                                  | -3378.077** | 1133.513 | -0.4547** | 0.2214 |
|                                  | Red                                                   | 34.4047 | 227.3303 | 0.0154 | 0.0436 |
| Area of Windows                  | Percentage of Window Area (Main Direction)           | 1901.015** | 321.7957 | 0.5420** | 0.0645 |
|                                  | Percentage of Window Area (Side Direction)            | 233.739 | 313.4042 | 0.2595** | 0.0538 |
| Usage (Standard: Single Family Home) | Apartment Building                                  | -2613.499** | 784.435 | -0.9295** | 0.1528 |
|                                  | Neighborhood Commercial                              | 2407.599** | 163.4737 | 0.5299** | 0.0317 |
|                                  | Cultural and Religious                               | -5069.985** | 1412.367 | -1.063‡ | 0.2760 |
|                                  | Retail and Entertainment                             | 4644.054** | 663.9175 | 0.7968** | 0.1300 |
|                                  | Public Welfare                                       | -1524.881* | 659.827 | -0.0716 | 0.1285 |
|                                  | Office                                               | 208.1505 | 788.2142 | -0.1584 | 0.1523 |
|                                  | Factory, etc.                                        | -1064.14 | 1107.872 | 0.0682 | 0.2219 |
| Surrounding Natural Environment  | Wind Speed                                            | -138.881* | 65.6492 | -0.0764* | 0.0355 |
|                                  | Temperature                                           | 882.4961 | 241.1278 | 0.1325** | 0.0508 |
|                                  | Humidity                                             | 111.3603 | 26.2164 | 0.0146 | 0.0055 |
|                                  | Surface Temperature of Buildings                      | 107.4262* | 50.7805 | 0.0498** | 0.0170 |
|                                  | Gradient                                             | -154.684** | 39.4433 | -0.1002** | 0.0068 |
| Basic Condition of Buildings     | Projected Lifespan of Buildings                       | -22.8484** | 7.2998 | 0.0043** | 0.0014 |
|                                  | Gross Area                                           | 7.6179** | 0.3986 | 0.0007** | < 0.0001 |
|                                  | Height                                               | 75.3672** | 24.7665 | 0.0210 | 0.0620 |
| Thermal Transmission of Buildings | Façade Area                                          | 1.2938† | 0.6662 | 0.0007† | < 0.0001 |
|                                  | S/V Ratio                                             | 0.1734 | 0.1235 | 0.0001† | < 0.0001 |
|                                  | W/D Ratio                                             | -51.6579 | 115.7059 | -0.0178 | 0.0220 |
|                                  | S/F Ratio                                             | 93.4634* | 44.1794 | 0.0456** | 0.0088 |
| Constant                         |                                                      | 10402.96* | 16764.86 | -8.4064* | 3.3537 |

< 0.1: †, < 0.05: *, < 0.01: **
4.3 Verification of Hypotheses

Based on the analysis results, the hypotheses established in Section 2 were verified: the analysis results of OLS and gamma regression were completely different. In the analysis result for the dependent variables, the histogram of the energy consumption of buildings shows a curve skewed to the left, which means it does not present a normal distribution. This study also examined OLS regression for logarithmic dependent variables, an analysis technique that is considered appropriate for this kind of distribution. In order for this method to be applied, logarithmic dependent variables should follow a normal distribution. However, various normality tests carried out in the study show that these figures did not present a normal distribution. Therefore, the most appropriate method for analyzing this data is gamma regression. It also turns out that the gamma regression has more explanatory power than does OLS, which makes it more suitable for the analysis of data in this study.

Second, most variables related to urban form and tissue bear a certain relation to the energy consumption of buildings. It is found that the orientation of buildings and width of the public space in front of buildings are relevant to the energy consumption of buildings, while the setback of buildings on the roadside, like a wedding cake shape, does not have an impact on the energy consumption of buildings.

Third, microclimate elements such as wind speed and humidity as well as temperature, a well-known factor, bear a close relation with the energy consumption of buildings. This study divided temperature into the ambient temperature of buildings and the temperature of the broader area, both of which have an impact on the energy consumption of buildings. In particular, the ambient temperature of a building has a huge impact on its energy consumption, which implies it should be properly managed.

4.4 Discussion

In spite of the above limitations, this study is meaningful in that it provides a basis for the management of the energy consumption of buildings. Considering the fact that building energy consumption, alongside transportation, plays an important role in creating sustainable cities, it is expected that an expansion of the research performed in this study will contribute to the development of a sustainable urban model. In particular, this study is meaningful in terms of considering external elements such as urban form and tissue and microclimate as factors affecting the energy consumption of buildings, as opposed to preceding research which only takes into account urban form and character. It is expected that the results of this study will help allow more elaborate management of the energy consumption of buildings.

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