Energy Proceedings
Vol 44, 2024
ISSN 2004-2965

Examining mechanisms linking urban contextual form to building energy use – An empirical study in Seoul

Parth Bansal [1], Steven Jige Quan [2*]

1 City Energy Lab, Graduate School of Environmental Studies, Seoul National University, South Korea

2 Environmental Planning Institute, Graduate School of Environmental Studies, Seoul National University, South Korea
(*Corresponding Author. Email: sjquan@snu.ac.kr | stevenchuan6656@gmail.com)

ABSTRACT

The link between urban contextual form and building energy use has been attracting attention in the field recently. Most studies measure urban form using a set of parameters, which are then used to explain building energy use variation. Typically, the results obtained are explained with a speculation on different mechanisms and their balances. However, such an approach does not quantify the contributions of individual mechanisms. This study uses mediation models to examine urban contextual form's influence on building energy use, using building solar insolation, context temperature, and context urban vitality as mediators. Summer electricity, winter electricity, summer gas, and winter gas use intensities are analyzed. The results show that mediators significantly influence various contextual variables, and their impact varies across seasons and types of energy use. These mediators can strengthen or undermine each other, influencing the net impact of contextual form. Thus, urban form energy efficiency interventions need to consider those mechanisms and their effects, considering the specific period and type of energy use.

Keywords: urban building energy, urban environment, urban context, building energy use mechanisms

1. INTRODUCTION

Energy use in urban areas has been receiving attention due to the increase in climate change concerns. Within urban areas, buildings are the major energy consumers, utilizing 20–40% of the total energy produced [1]. Thus, the effects of building design and function on its energy use have been extensively studied for the development of building design codes. Recently, studies have focused on understanding building energy use at a larger scale ranging from the neighborhood to urban scale. These studies typically focus on explaining building energy use by urban form parameters [2] or typologies [3]. However, while the urban contextual form's direction and magnitude of the effects have been extensively studied, the contribution of different mechanisms linking urban contextual form to building energy use is not well understood.

This study aims to fill this gap in the literature by introducing solar insolation, contextual temperature, and urban vitality as the mechanisms that link urban context to building energy use. The results show how these mechanisms either strengthen or undermine each other, influencing the net impact of contextual form variables. Furthermore, they reveal variations in these contributions across different seasons and types of energy use. The findings also show the residual direct effects of contextual factors, indicating the need for further investigations of a broader range of mechanisms.

2. LITERATURE REVIEW

Studies have investigated the influence of urban context on building energy use using either simulation or empirical measurements to answer the following major questions. What is the extent of contribution that urban form has on building energy variation? What is the direction and magnitude of effect urban form features or typologies have on building energy use? What mechanisms link urban form to building energy use?

For the first question, studies have reported different values depending on the location and study methodology [4]. Ratti et al. [5] found contextual form explained 10%, Quan et al. [6] -7.7-16.6%, and Bansal and Quan [3] 13.2-16.2% variation in building energy use. Quan and Li [4] summarized that studies generally

This is a paper for 15th International Conference on Applied Energy (ICAE2023), Dec. 3-7, 2023, Doha, Qatar.

indicate a range of 105-200% in magnitude compared to the baseline of minimal energy use.

For the second question, studies have used diverse sets of urban form indicators or different urban typologies to link urban form and building energy. Wilson [7] found that increasing contextual density decreases electricity use. Li et al. [2] found that while an increase in contextual density reduced electricity use for single-family housing, it actually increased electricity use for apartment-style housing.

For the third question, studies have considered three potential mechanisms, solar insolation (SI), contextual temperature (CT), and urban vitality (UV). Urban form determined the magnitude and duration of SI a building will receive in a given geographic setting [8]. Typically, dense and uniform urban form is associated with a low level of SI [9]. However, both low and excessive SI is associated with higher energy use [10]. At low SI, more energy is required for lighting and heating. Comparatively, excessive SI can cause overheating within building space and thus require more cooling energy [11]. Also, urban form has a major influence on microclimate due to differences in the permeability of SI in the outdoor environment [12].

Typically, denser areas are associated with higher CT due to the urban heat island effect, which can increase cooling or decrease heating demand [3]. However, the effect on building energy use can also be complex and nonlinear due to micro-scale differences in temperature [13].

UV mechanism has received relatively lower attention within the urban building energy literature. This mechanism links the building to its contextual form through human behavioral changes. The outdoor environment can induce or discourage outdoor activity and can cause changes in building occupancy duration [4]. In empirical studies, consideration for urban vitality has been limited to the inclusion of contextual socio-economic features [2], while simulation studies typically extrapolate human behavior from individual buildings without considering changes due to urban form.

The literature on urban building energy use has extensively investigated the influence of contextual form using different sets of features or typologies. However, the actual mechanism by which contextual features influence building energy use has received limited attention. Thus, using mediation models, this study investigates different mechanisms through which urban form relates to energy use intensity.

3. METHODOLOGY

3.1 Study score

Seoul is the largest city in South Korea, and extends over 605 KM^2 with an average population density of 16,000/KM^2. Its urban form is characterized by spatially dense and low- to mid-rise housing, slab-style apartments, and tower-style office buildings. Seoul is classified as Dwa by the Köppen climate classification, with a typical humid summer and dry winter. Fig. 1 shows the mean, average high, and average low temperatures for 2022.

Residential building electricity and gas EUI (energy use per floor space) for the year 2022 are analyzed in this study. Electricity and gas EUI for summer (Jun-Aug) and winter (Dec-Feb) were analyzed separately because they are typically used for different residential functionalities. The periods of summer and winter seasons were based on the temperature profile of the study area.

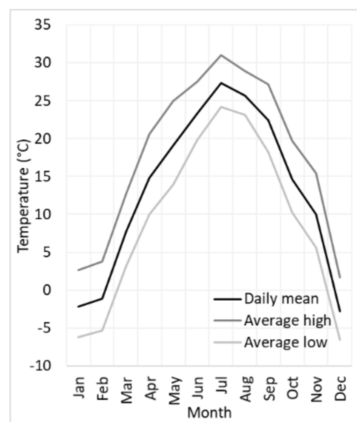

Fig. 1. Temperature profile of the study area in 2022.

3.2 Data collection and organization

Residential building energy use data consisting of monthly electricity and gas use was collected from the government portal [14]. The dataset is at the plot-level spatial unit. It consists of multi-unit residential plots where the number of households exceeds 300. The samples for which electricity or gas data were missing for any of the months during 2022 are removed. This data was used to calculate summer and winter – electricity and gas EUI by dividing the total energy use of a plot by the total floor space in a plot.

All the datasets for this study were collected from secondary sources, except for solar insolation, which was estimated using simulation. The total sample size was 3,157 plots after removing plots with partially missing energy data and plots with no nearby temperature sensor. Table 1 provides a summary of the variables.

Table 1. Descriptive statistics of the study variables.

Variable		Mean	SD	Min	Max	Unit	Description
Dependent variable							
Energy use	Summer electricity EUI	43.26	28.55	16.24	102.87	kWh/m^2	Electricity use intensity in summer.
	Winter electricity EUI	39.58	19.84	12.48	91.33	kWh/m^2	Electricity use intensity in winter.
	Summer gas EUI	2.84	0.78	0.92	5.18	kWh/m^2	Gas use intensity in summer.
	Winter gas EUI	67.56	23.68	7.97	131.27	kWh/m^2	Gas use intensity in winter.
Independent variable							
Plot-level features	Building cover percentage	47.57	10.92	11.96	75.22	%	Percentage of area occupied by building footprints.
	Building height	34.12	8.13	9.02	85.86	m	Mean height of buildings.
	Building age	24.95	11.24	4.95	56.49	years	Building age in the year 2022.
	Real estate price	37.94	15.42	5.05	93.95	100,000 KRW/m^2	Estimated real estate price per m^2 of floor space.
Contextual-level features	Building height	28.92	14.95	8.51	63.58	m	Mean height of buildings.
	Building height variation	4.54	2.21	0.38	6.13	m	Standard deviation of building height
	Building cover percentage	36.15	14.15	10.95	55.24	%	Percentage of area occupied by building footprints.
	Green cover percentage	10.15	24.96	0	59.94	%	Percentage of area occupied by green areas.
	Water cover percentage	0.68	18.95	0	41.59	%	Percentage of area occupied by waterbody.
Mediation features	Summer solar insolation	0.95	0.28	0.42	1.26	kWh/m^2	Mean hourly solar insolation intensity in summer
	Winter solar insolation	0.72	0.21	0.29	1.01	kWh/m^2	Mean hourly solar insolation intensity in winter
	Summer context temperature	0	1.71	-8.20	6.45	°C	Difference in temperature from city mean in summer
	Winter context temperature	0	1.06	-4.45	5.05	°C	Difference in temperature from city mean in winter
	Urban vitality	68.34	14.95	14.82	94.51	N/A	Street smart walk score

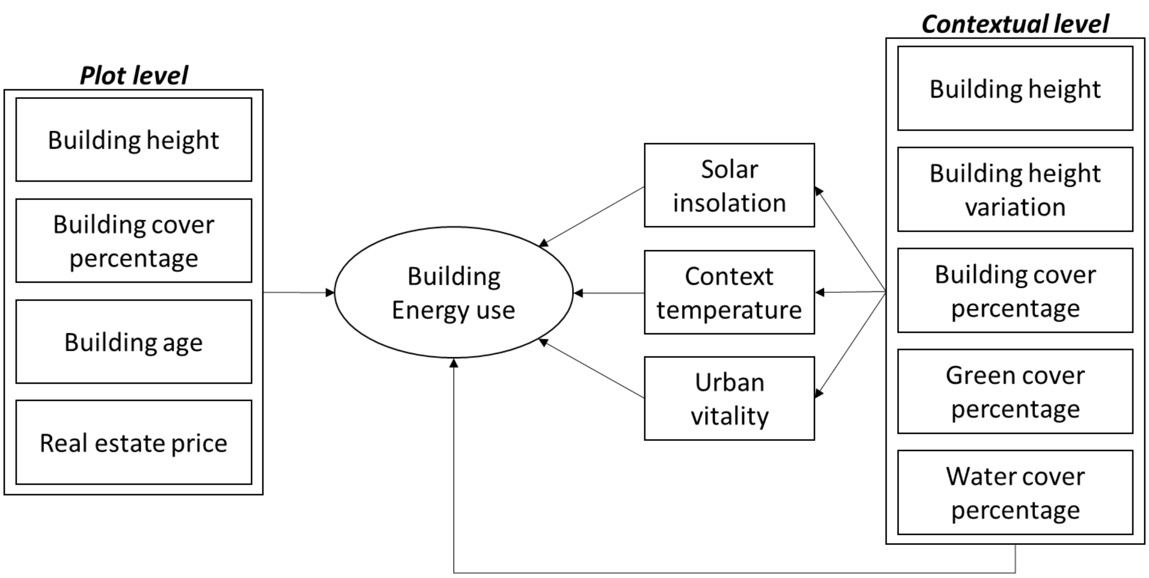

Fig.2. Conceptual framework of the study.

3.3 Model specification

An ordinary least square (OLS) based mediation model is used to analyze summer and winter – electricity and gas EUI independently. Figure 2 shows the conceptual diagram of the mediation model used.

$$SI = i_{SI} + b_i^1 CL_i + e_{SI} \quad (1)$$

$$CT = i_{CT} + b_i^2 CL_i + e_{CT} \quad (2)$$

$$UV = i_{UV} + b_i^3 CL_i + e_{UV} \quad (3)$$

$$EUI = i_{EUI} + b_i' CL_i + b_j PL + b_k SI + b_l CT + b_m UV + e_{EUI} \quad (4)$$

Where SI, CT, and UV refer to mediator variables solar insolation, context temperature, and urban vitality, respectively. CL, and PL are contextual level and plot level variables, and EUI is the dependent variable referring to summer electricity, winter electricity, summer gas, or winter gas energy use intensity. b_i' is the direct effect of contextual level variables. $b_i^1 * b_k$,

$b_i^2 * b_l$, and $b_i^3 * b_m$ are the indirect effects of the contextual level variable through SI, CT, and UV, respectively.

4. RESULTS

4.1 Electricity models

Table 2 shows the results for the electricity models. Solar insolation is a significant mediator for all five contextual variables in both the summer and winter seasons. It mediated 28.35% to 38.80% and 37.21% to 92.04% of the effect contextual variables had in summer and winter, respectively. Contextual temperature is also a significant mediator in the summer season for all five context variables and mediated 25.20% to 58.87% of the effect contextual variables had in summer. In winter, the contextual temperature is an insignificant mediator for any of the five contextual variables. Finally, urban vitality is a significant mediator for only GCP and WCP in both the summer and winter seasons. It mediated 27.74% and 19.57% in summer and 18.53% and 16.50% in winter for GCP, and WCP, respectively.

4.2 Gas models

Table 3 shows the results for the gas models. In summer, all three mediators are insignificant for any of the five contextual variables, and the direct effect is also generally insignificant, except for WCP, which is marginally significant. Comparatively, in winter, solar insolation is a significant mediator for BHV, mediating 62.77% of the effect. Contextual temperature is a significant mediator of BH, GCP, and WCP, mediating 22.44%, 60.07%, and 53.94% of the effect, respectively. Urban vitality is also a significant mediator of GCP, and WCP, mediating 22.21%, and 22.81% of the effect, respectively.

5. CONCLUSION

This study investigated the relationship between urban contextual form features and residential building EUI using solar insolation, contextual temperature, and urban vitality as mechanisms linking contextual form to building energy use. Specifically, summer electricity, winter electricity, summer gas, and winter gas EUI were investigated using OLS based mediation models with emphasis on the effects of contextual BH, BHV, BCP, GCP, and WCP. The result shows that all three mediators studied can significantly mediate the effects of contextual variables, depending upon the type of energy use and season. For electricity, solar insolation mediated 36.25% and 78.35%, contextual temperature 52.07% and 6.61%, and urban vitality 6.74% and 4.73% of the total effect for summer and winter, respectively. For gas, contextual variables were generally insignificant, while in winter, 37.89%, 36.92%, and 11.28% of total effects were mediated by solar insolation, contextual temperature, and urban vitality, respectively. Direct effect account for 4.93%, 10.29%, and 13.89% of the total effect for summer electricity, winter electricity, and winter gas, respectively.

Table 2. Results of electricity models

Variable	Summer				Winter			
	Indirect effect			Direct	Indirect effect			Direct
	SI	CT	UV		SI	CT	UV	
Building height	-0.139***	0.224***	0.013	0.097**	0.346***	-0.018	0.006	0.072
Building height variation	1.849**	-2.806***	-0.087	-0.024	-2.649***	0.104	-0.039	-0.087
Building cover percentage	-0.109**	0.212***	0.049	0.015	0.132**	0.013	0.022	0.094*
Green cover percentage	0.211***	-0.164***	-0.181***	-0.095*	-0.163***	0.092	-0.081**	0.102**
Water cover percentage	0.232***	-0.243**	-0.143**	-0.115**	-0.142***	-0.064	-0.060*	0.096*

Table 3. Results of gas models

Variable	Summer				Winter			
	Indirect effect			Direct	Indirect effect			Direct
	SI	CT	UV		SI	CT	UV	
Building height	-0.010	-0.013	0.001	0.004	0.098	-0.059**	0.008	0.097*
Building height variation	-0.137	0.164	0.001	0.004	-0.747*	0.338	-0.053	-0.052
Building cover percentage	0.008	-0.012	-0.001	-0.014	0.037	0.04	0.030	-0.115**
Green cover percentage	-0.016	0.010	0.003	0.028	-0.046	0.298***	-0.110**	0.042*
Water cover percentage	-0.017	0.014	0.002	0.071*	-0.040	-0.207***	-0.088*	0.049*

The results also showed that for many contextual variables, the mediated effects could undermine each other, reducing the magnitude and significance of the total effect. This indicates that urban planning interventions targeted at mediators can have significant energy sustainability-related externalities. For example, pavement material with lower absorptions has been suggested for reducing urban heat island [15]. This can reduce contextual temperature, which would indirectly reduce the increase in summer electricity EUI due to an increase in contextual building height.

More studies in other climate regions are needed to understand the variability in mediated effect and the extent of effect mediated by different mechanisms. Future improvements in data sources can further refine contextual form, mechanism, and building level variables measurements, which can improve the model's strength.

ACKNOWLEDGMENT

This work was supported by the Creative-Pioneering Researchers Program through Seoul National University (SNU), the National Research Foundation of Korea (NRF) grant funded by the Korea government (Ministry of Science and ICT) (No. 2018R1C1B5043758; No. 2022R1C1C1004953), and the National Research Foundation of Korea (NRF) grant funded by the Korea government (Ministry of Education) (No. 5120200113713).

DECLARATION OF INTEREST STATEMENT

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

REFERENCE

[1] Pérez-Lombard L, Ortiz J, Pout C. A review on buildings energy consumption information. Energy and Buildings. 2008;40:394-8.

[2] Li C, Song Y, Kaza N. Urban form and household electricity consumption: A multilevel study. Energy and Buildings. 2018;158:181-93.

[3] Bansal P, Quan SJ. Relationships between building characteristics, urban form and building energy use in different local climate zone contexts: An empirical study in Seoul. Energy and Buildings. 2022;272:112335.

[4] Quan SJ, Li C. Urban form and building energy use: A systematic review of measures, mechanisms, and methodologies. Renewable and Sustainable Energy Reviews. 2021;139:110662.

[5] Ratti C, Baker N, Steemers K. Energy consumption and urban texture. Energy and Buildings. 2005;37:762-76.

[6] Quan SJ, Economou A, Grasl T, Yang PP-J. An exploration of the relationship between density and building energy performance. URBAN DESIGN International. 2020;25:92-112.

[7] Wilson B. Urban form and residential electricity consumption: Evidence from Illinois, USA. Landscape and Urban Planning. 2013;115:62-71.

[8] Knowles RL. The solar envelope: its meaning for energy and buildings. Energy and Buildings. 2003;35:15-25.

[9] Cheng V, Steemers K, Montavon M, Compagnon R. Urban form, density and solar potential. The 23rd Conference on Passive and Low Energy Architecture. 2006.

[10] Chi DA, Moreno D, Navarro J. Correlating daylight availability metric with lighting, heating and cooling energy consumptions. Building and Environment. 2018;132:170-80.

[11] Valladares-Rendón LG, Schmid G, Lo S-L. Review on energy savings by solar control techniques and optimal building orientation for the strategic placement of façade shading systems. Energy and Buildings. 2017;140:458-79.

[12] Oke TR, Mills G, Christen A, Voogt JA. Urban climates: Cambridge University Press; 2017.

[13] Gros A, Bozonnet E, Inard C. Cool materials impact at district scale—Coupling building energy and microclimate models. Sustainable Cities and Society. 2014;13:254-66.

[14] National Spatial Data Infrastructure Portal. http://www.nsdi.go.kr. Accessed on January 2023

[15] Gago EJ, Roldan J, Pacheco-Torres R, Ordóñez J. The city and urban heat islands: A review of strategies to mitigate adverse effects. Renewable and Sustainable Energy Reviews. 2013;25:749-58.