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Correspondence Between Urban Form Typology and Residential Building Energy Use Patterns in Seoul

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ABSTRACT

With the increasing availability of urban factors and building energy datasets, more studies have emerged in the urban building energy field examining the urban form–energy relationship to support energy-oriented urban planning and urban energy system management. However, two limitations exist in current studies: the oversimplified quantification of urban form and the lack of consideration of temporal energy use pattern. Recent studies focused more on urban and building factors that are theoretically relevant to building energy, but how these factors are related to energy use patterns is still far from clear. This study aims to fill this research gap by examining the relationship between urban form typology and residential building energy patterns in Seoul using clustering and the Sankey diagram. The study used the Gaussian mixture model to identify four typical urban form typologies based on energy-relevant urban factors and *k*-shape clustering to detect three distinct monthly primary energy use patterns of residential buildings. The urban form typologies and energy use patterns are then compared through the Sankey diagram. The comparison shows a complex correspondence. The Mid-rise Open typology achieves a general balance among the three patterns, while the Mid-rise High-density typology, Low-rise Compact typology, and High-rise Low-density typology are all dominated by a U-shaped pattern with a varying balance between the Flat pattern and W-shaped pattern. The findings of this study depict the correspondence between urban form typologies and building energy use patterns, which are highly interpretable and thus informative for energy-oriented urban planning and energy system management toward sustainable urban development.

Keywords: urban building energy, urban morphology, urban energy system management, Gaussian mixture model, *k*-shape clustering

1. INTRODUCTION

Energy efficiency in cities is becoming more critical, especially in the new paradigm of carbon neutral strategy against climate change. Given the increasing availability of urban factors and building energy datasets, more studies have emerged in the urban building energy field and have primarily focused on urban form–energy relationship studies [1]. However, two limitations exist in current studies: the oversimplified quantification of urban form and the lack of consideration of temporal energy use pattern.

Urban form is generally described in two ways in the urban form–energy relationship studies, form indicators and form typologies, both of which are in a highly simplified manner. Urban form indicators adopted in previous studies include housing size [2], density (population or dwelling unit density)[3, 4], surface area to volume ratio [5]. Urban form typologies were often defined as hypothetical urban forms with specific building typologies [6, 7], or empirical types such as housing types [8], buffered buildings [7] neighborhoods [9, 10], or buffered neighborhoods in limited case study areas [11, 12]. These approaches mostly oversimplified urban forms as simple indicators or defined typologies manually with limited consideration of general urban form typologies in cities. Such approaches are limited in the representation of urban form in previous studies.

Another limitation of previous studies is the lack of consideration of temporal patterns of building energy use. Most of the previous studies examined annual or seasonal energy use separately, without considering the temporal variation of energy use which is one of the focuses in urban energy system management. This presents a gap between urban form-energy studies and the urban energy management practice, limiting the implication of those studies.

These two limitations can be addressed by referring to relevant fields, such as urban morphology and urban energy system. In urban morphology, scholars applied clustering methods, such as *k*-means clustering [13], hierarchical clustering [14], and model-based clustering [15], to identify different urban form typologies. In urban energy system management studies, clustering methods were also extensively used to find the typical daily, seasonal, or annual energy use patterns of buildings. Among them, *k*-means is the most popular algorithm, and when time-series data is considered, shape-based clustering has been proved to be more efficient. McLoughlin, Duffy [16] applied *k*-means and *k*-medoid clustering and self-organizing maps to extract ten common daily electricity use patterns in households and analyze household characteristics, though without mentioning building or urban contexts. Hsu [17] compared cluster-wise regression, *k*-means, and model-based clustering methods with linear regression in multifamily buildings in New York City to predict building energy consumption levels. Jota, Silva [18] used hierarchical clustering to forecast daily load and peak demand levels for a large public hospital in Brazil. Yang, Ning [19] adopted shape-based clustering for energy pattern recognition. They found that *k*-shape clustering outperformed dynamic time-warping clustering in ten institutional buildings concerning daily patterns developed building energy forecasting models. While these studies provided insightful findings upon urban form typologies and building energy use patterns, few studies examined how energy usage patterns relate to urban form typologies by connecting the two streams.

The main contribution of this study is that it, for the first time (to the best of the authors' knowledge), depicts the correspondence between urban form typologies and building energy use patterns, which are highly interpretable and thus informative for efficient energy system management and energy-oriented urban planning for sustainable urban development.

The study hypothesis is that residential building energy use patterns vary among urban form typologies. To verify the hypothesis, this study identified urban form typologies based on 13 energy-relevant factors, after which monthly primary energy use patterns were extracted from residential buildings. Finally, the ratios of patterns in urban form typologies were examined.

Table 1. Energy-relevant urban form factors.

Division	Urban form indicator	Unit	Measure target	Description
Urban context	Coverage ratio (CR)	n/a	Urban context	Total building footprint areas in the cell to the cell area.
	Sky view factor (SVF)	n/a	Urban context	The ratio of the visible sky from an observation point on average in the cell.
	Urban porosity	n/a	Urban context	Based on the highest building in the cell, the total volume excludes building volumes and is divided by the total volume.
	Surface roughness	m	Urban context	The standard deviation of building heights in the cell.
	Vegetation area ratio	n/a	Urban context	The vegetation area to the cell area.
	Water body area ratio	n/a	Urban context	The water body area to the cell area.
	Active population density	N/m^2	Urban context	The population density at 3 pm presents the active population density in the cell.
Building	Surface to volume ratio (S/V)	m^{-1}	Residential buildings	Surface to volume ratio in the cell on average.
	Building height	m	Residential buildings	Average building height of buildings in the cell.
	Convex ratio	n/a	Residential buildings	The average ratio each building footprint area to its convex hull area in the cell.
	Building age	Years	Residential buildings	The average residential building age in the cell.
Occupant	Land price	won/m^2	Residential buildings	The land price per square meter of residential buildings in the cell on average.
	Residence density	N/m^2	Residential buildings	The population density at 3 am presents the residence population density in the cell.

Note: won is the unit of Korean currency. N is the number of samples.

2. RESEARCH SCOPE AND DATA

The study area is Seoul, a highly dense city in the Republic of Korea, covering about 605 km^2. The unit of analysis is the 500 m × 500 m grid, often referred to as a neighborhood scale [20]. A grid-based analysis is used because it allows for consistent scale comparisons across cities and is feasible for data integration in a cell [21].

The analysis time range of building energy use is from January to December 2019. The urban form measurements shown in Table 1 are selected based on the three main effects regarding building energy use: urban context effects related to microclimate, shading effects, and solar access; building effects referring to materials that affect heat loss and solar gain; and human behavior effects. System effects are not considered due to data availability. Building electricity and gas usage are provided in monthly format by the Ministry of Land, Infrastructure, and Transport [22]. The energy use of a residential building is converted to primary energy, based on the coefficient provided by the Korea Energy Corporation in 2019 [23]. The building's energy use intensity (EUI) is the building's primary energy use normalized by the building's entire floor areas.

3. METHODS

The study hypothesis is that building energy use patterns vary according to urban form typologies. The study tests the idea in four stages. First, Seoul was divided into 500 m × 500 m grids and 406 cells with residential building energy data were selected as urban form study areas. Second, the grids were clustered using 13 energy-relevant factors in the Gaussian mixture model (GMM). Third, the energy use patterns from January to December were detected by *k*-shape clustering based on Euclidian distance measurements. Fourth, the study examined whether the urban form typology correspondence to residential energy use patterns.

The sklearn.mixture [24] and tslearn [25] packages in Python were used to implement the GMM and *k*-shape clustering in Python version 3.8.5. Data visualizations were conducted in Tableau, Rhino, and Grasshopper.

4. RESULTS

4.1 Urban form typology

The GMM results indicate four urban form typologies in Seoul (Table 2). Typology 2 is the most common urban form typology at 45%, meaning a Low-rise Compact typology, followed by Typology 1 at 20%, suggesting a Mid-rise High-density typology. Typologies 3 and 4 have comparable sample sizes, implying a Mid-rise Open typology and a High-rise Low-density typology, respectively (Fig. 1).

4.2 Residential building energy use pattern

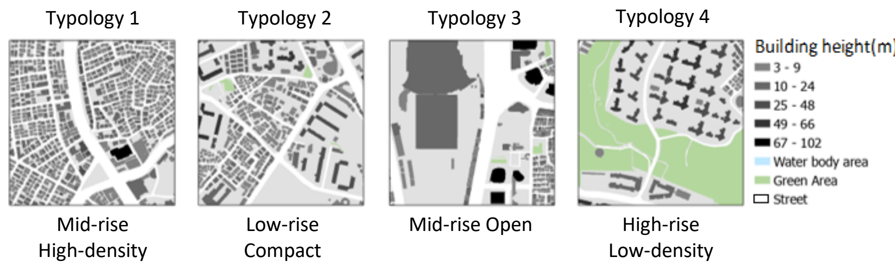
Three distinct energy use patterns were identified in Seoul. The most common pattern is Pattern 2 at 56%, followed by Pattern 3 at 27%, and the least common one is Pattern 1 at 17% (Table 3). Pattern 1 is a Flat pattern and a comparatively flat curve and is mostly unaffected by air temperatures. Energy use is relatively constant throughout all months (Fig. 2). Pattern 2 is a U-shaped pattern. Winter (January, February, December) energy usage is much greater than summer (July, August, September). Pattern 3 shows a W-shaped pattern, similar to the U-shaped pattern (Pattern 2), but greater energy consumption throughout spring (March, April, May) and fall (September, October, November) seasons, with greater peak energy consumption appearing during summer compared to the U-shaped (Pattern 2).

4.3 Comparisons of urban form typology and residential building energy use patterns

As shown in Fig. 3, no simple correspondence is found between urban form typologies and residential energy use patterns. The predominant energy use pattern in the Mid-rise High-density typology (Typology 1), the Low-rise Compact typology (Typology 2), and the High-rise Low-density typology (Typology 4) is the U-shaped pattern (Pattern 2) as its proportion exceeds 50%. The second greatest proportion pattern in the Mid-rise High-density typology (Typology 1) and the Low-rise Compact typology (Typology 2) is the W-shaped pattern (Pattern 3) at 23% and 32%, respectively. In contrast, in

Table 2. Mean values of urban form factors and the number of samples in urban form typologies.

Typology	CR	SVF	Urban porosity	Surface roughness	Vegetation area ratio	Water body area ratio	Active population density	S/V	Building height	Convex ratio	Building age	Land price	Residence density	Number of samples
	n/a	n/a	n/a	m	n/a	n/a	N/m^2	m^{-1}	m	n/a	Years	won/m^2	N/m^2	(N)
1	0.20	0.82	0.96	7.32	0.29	0.03	0.02	7.78	8.85	0.96	29.07	2636892	0.02	83
2	0.30	0.73	0.94	8.04	0.04	0.00	0.03	8.43	10.10	0.96	27.3	3346580	0.03	184
3	0.17	0.81	0.95	17.69	0.09	0.01	0.03	14.12	26.72	0.91	26.93	4611197	0.03	73
4	0.09	0.88	0.96	15.81	0.33	0.07	0.02	17.71	34.70	0.88	22.72	2234559	0.02	66



a

b

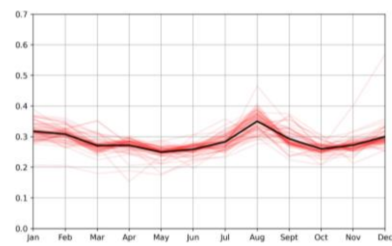
Fig. 1. Representative urban form typologies: a) typical urban form typology maps; b) 3D visualizations.

the Low-density typology (Typology 4), the second greatest proportion pattern is the Flat pattern (Pattern 1), at 24%. The Mid-rise Open typology (Typology 3) achieves a general balance among the three patterns.

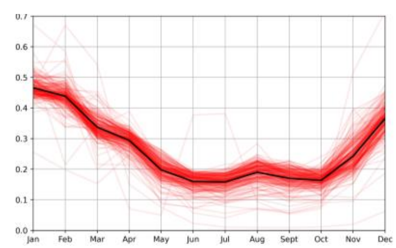
5. DISCUSSION

By comparing urban form typologies and residential building energy use patterns, this study confirms the hypothesis that residential building energy use patterns vary across urban form typologies. Although urban form typologies have mixed energy patterns, the ratios indicate trends for each urban form typology: The Mid-rise Open typology (Typology 3) achieves a general balance among the three patterns. The Mid-rise High-density typology (Typology 1), Low-rise Compact typology (Typology 2), and High-rise Low-density typology (Typology 4) are dominated by a U-shaped pattern (Pattern 2) with a varying balance between the Flat (Pattern 1) and W-shaped (Pattern 3) patterns.

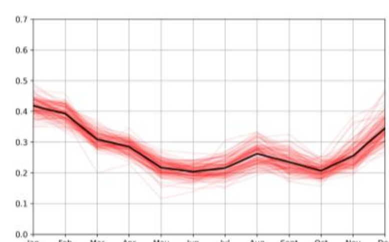
1. Why do U-shaped (Pattern 2) and W-shaped pattern (Pattern 3) predominate in residential buildings? Seoul's climate is humid continental with four distinct seasons. As shown in Fig. 2, it is in January that most energy is consumed, with typically the lowest temperatures of the year in Seoul. The temperature



Flat pattern (Pattern 1)



U-shaped pattern (Pattern 2)



W-shaped pattern (Pattern 3)

Fig. 2. Residential energy use patterns.

Table 3. Average EUI (kWh/m^2) for all months and number of samples in patterns.

Patterns	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.	Annual average	Number of samples (N)
1	29.87	28.13	22.00	19.63	13.99	11.94	12.13	14.77	13.06	12.13	16.56	23.78	18.17	68
2	63.62	59.83	46.26	43.19	31.98	30.45	32.42	39.20	35.41	31.68	40.58	53.60	42.35	228
3	233.50	264.69	209.35	129.48	101.32	91.07	95.23	110.31	97.22	86.34	100.90	139.83	138.27	110

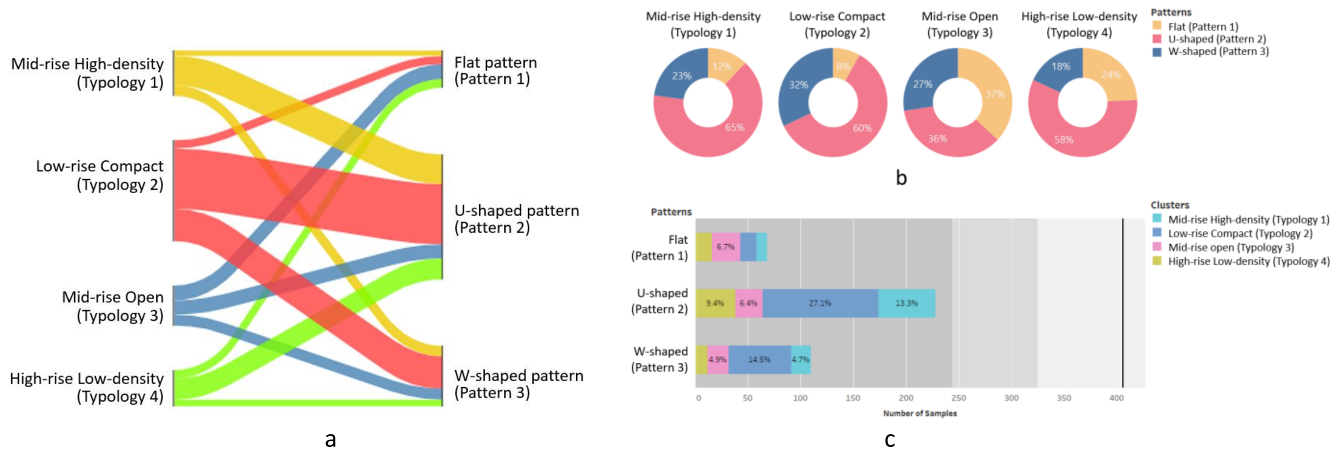


Fig. 3. a) Sankey diagram for partitioning bundles based on urban form typologies and energy use patterns; b) proportion of energy use patterns in urban form typologies; c) proportion of urban form typologies in energy use patterns.

variations between the hottest days in summer and the coldest days in winter are extreme.

2. Which energy pattern is most advantageous and disadvantageous? The answer is the Flat pattern (Pattern 1), where energy usage patterns are generally flat, and the monthly average EUI is lowest at 18.17 kWh/m^2. The most disadvantageous pattern is the W-shaped pattern (Pattern 3), with an average monthly EUI of 138.27 kWh/m^2 (Table 3), much more significant than the other patterns, with two peak times that may place a strain on the power system.

3. Which urban form typology does offer the best energy prospects, and what does distinguish it? The Mid-rise Open typology (Typology 3) has the highest energy performance in terms of residential energy use patterns, followed by the High-rise Low-density typology (Typology 4). These two urban form typologies share a low building coverage ratio, a low SVF, a high surface roughness, a high building height, a low surface-to-volume ratio, and a low convex ratio. The Mid-rise Open typology has the highest land prices, whereas the High-rise Low-density typology has the lowest land prices and a high vegetation cover ratio (Table 2).

6. CONCLUSION

More studies have focused on the urban building energy field, examining the urban form–energy relationship. However, two limitations exist in current studies: the oversimplified quantification of urban form and the lack of consideration of temporal energy use pattern. Recent studies focused more on urban and building factors that are theoretically relevant to building energy, but how these factors are related to energy use patterns is still far from clear. At the same time, many studies in the relevant fields of urban morphology and urban energy system management applied the clustering method to identify urban form typologies and energy use patterns. This research aims to fill the current research gap in form-energy studies by referring to the advances in those fields to examine the relationship between urban form typology and residential building energy patterns in Seoul using clustering and the Sankey diagram. The study identified four urban form typologies based on 13 energy-relevant factors through GMM clustering and three primary energy use patterns from residential building monthly usage through *k*-shape clustering. Finally, pattern ratios in urban form typologies were studied. While no simple correlation could be found between the two, the Mid-rise Open typology achieves a general balance among the three patterns. The U-shaped pattern dominates the Mid-rise High-density typology, Low-rise Compact typology, and High-rise Low-density typology, with different Flat and W-shaped patterns ratios.

A limitation of this study is that it disregards air temperature differences in the spatial distribution of Seoul. Nonetheless, for the first time (to the best of the authors' knowledge), the findings here depict the correspondence between building energy use patterns and urban form typologies, which are highly interpretable and thus informative for efficient energy system management and energy-oriented urban planning toward sustainable urban development.

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