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Effect of New Progressive Tariff on Electricity Use in Seoul Apartments: Evidence from Multisource Big Data and Urban Geospatial Data

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ABSTRACT

A new electricity progressive tariff (PT) was introduced to South Korea in 2017 to alleviate financial burden of households from air conditioning use in hot summers. Although people were concerned that this policy may lead to additional household energy use across the year, very limited evaluations have been conducted partially due to the lack of extensive and targeted datasets. This study examines how the new PT influences residential electricity use in different apartments in Seoul. A combined dataset was collected from both multisource big data and urban geospatial data. The significance of household electricity use changes of 402 apartments was estimated based on the dataset with interrupted time series analysis. Relationships between the significance of change and energy use, household socioeconomic status, and built environment of apartments and neighborhoods were further examined using logistic regression. Results showed that significant changes are likely to occur with reduced previous electricity use, high adult male ratio, and high apartment density. The findings of this study can help policymakers further evaluate the new policy for sustainability goals, including social welfare, urban energy, and economic development.

Keywords: progressive tariff, energy policy evaluation, residential electricity use, energy use behavior, interrupted time series analysis, built environment

1. INTRODUCTION

Summers in South Korean cities have intensified in recent years with long and severe heatwaves. Increasing electricity demand for air conditioning use adds financial burden to households, especially under the existing electricity progressive tariff (PT) system, which sets a high price with additional electricity use in a block-division manner. The issue of compromised household basic need of thermal comfort has led to the development and implementation of a new PT in 2017 by the Korean government and Korea Electric Power Corporation to improve affordability of electricity. Compared with the previous system, the new PT has less blocks and generally lower electricity price. Since its establishment over three years ago, issues on whether the new PT has reached its initial goal and led to increased residential electricity use across the year as a side effect remain unclear. Few studies discussed those questions for this policy change in South Korea [1].

Many studies have examined the effect of a new PT, including public acceptance [2] and actual electricity use changes [3], in different countries. The literature shows diverse findings on price elasticity of electricity use in different price blocks [4, 5], income groups [4, 6-8], and their combinations [3]. Very few studies have compared age groups and found electricity use of older households are remarkably sensitive to price schemes in PT [7].

However, the three main limitations of previous studies are as follows. First, most of them neglected built environment factors that may contribute to household energy use changes. Built environment of apartments and neighborhoods can create barriers or attractions for people to perform outdoor activities in their leisure time. For example, tall buildings may discourage residents to go outdoors while walkable and vibrant neighborhoods can encourage people to enjoy parks, street stores, and cafés. The opportunity for outdoor activities can reduce indoor time and provide residents additional options for going outside to save on their electricity bills. Second, the gradual change of energy use behavior is largely ignored. Previous studies typically adopted models that simplified complex and gradual processes as sudden changes, which raises validity concerns in their findings. Third, previous studies generally focused on the newly established PT from normal pricing schemes and very few investigations examined the new PT as a relaxation of the previous PT to reduce electricity costs.

This work aims to solve research gaps of previous studies by examining the influence of the new PT system on electricity use in different Seoul apartments. This study used a combined dataset from multisource big data and urban geospatial data. The dataset contains not only household socioeconomic characteristics but also built environment characteristics of apartments and their neighborhoods. Moreover, this study applied interrupted time series (ITS) analysis to understand both abrupt and gradual changes in household electricity use after the new PT. The logistic regression model was used to examine the influence of previous electricity use, household characteristics, and built environment on energy use changes.

2. METHODOLOGY

2.1 *Study area and samples*

Seoul, the largest and capital city of South Korea, is the study area of this work. Seoul has an area and very high population density of 605.2 km^2 and 16,181 people/km^2, respectively. The city has four seasons, with hot and humid summers as well as cold and dry winters. This study focuses on apartments, a main residential housing type in Seoul. The unit of analysis is individual apartment parcel. A total of 402 apartments were selected as samples based on data availability (Figure 1).

2.2 *Variable selection and data collection*

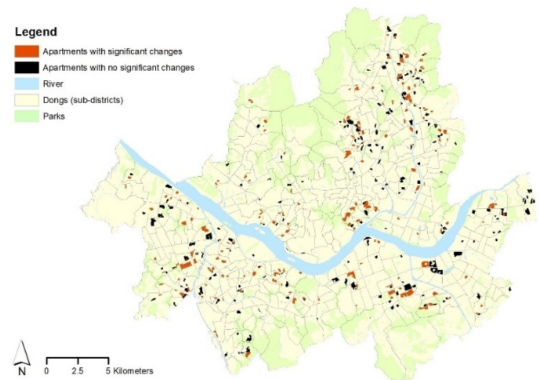

Figure 1. Seoul apartment parcel samples in this study.

Apart from apartment ledger and monthly weather condition data as common data provided by the Korean government, two types of main data sources were utilized in this study, namely, multisource big data and urban geospatial data. Big data was collected from three resources, namely, monthly electricity use data at the parcel level from the Seoul Building Energy dataset; de facto population data from the De Facto Population database; and apartment transaction price data from the Ministry of Land, Infrastructure, and Transportation. Urban geospatial data contain buildings, parcels, and urban parks in the GIS format from the Seoul Open Data. Data were preprocessed in Python and GIS.

On the basis of the dataset, this study defines two sets of dependent and independent variables for two analytical steps. Dependent variable in the first set is the average monthly household electricity use while its independent variables contain monthly heating degree days and cooling degree days. Also included are a level variable indicating each month before and after the new PT as 0 and 1, respectively, and a trend variable starting from 0 as the month index after the new PT.

Table 1. Descriptive statistics for the logistic regression model.

Type	Variable name	Variable description	Min	Max	Mean	Std
Dependent	**Change**	Change of household electricity use (significant: 1, otherwise: 0)	0	1	0.47	0.50
Energy use	**HH electricity**	Average monthly household electricity use before new PT (kWh)	7.67	1587.00	401.78	155.11
Household characteristics	**HH area**	Average household area (m^2)	37.63	267.58	102.12	25.49
	Housing price	Average unit housing price from 2011–2019 (1,000,000 KWR/m^2)	3.46	18.71	6.95	2.79
	Male ratio	Average male adult ratio from 2017–2019 (adult: 15–65 years old)	0.25	0.51	0.35	0.04
	Female ratio	Average female adult ratio from 2017–2019 (adult: 15–65 years old)	0.30	0.60	0.37	0.03
	Elderly ratio	Average elderly ratio from 2017–2019 (elderly: over 65 years old)	0.07	0.35	0.16	0.04
Apartment built environment	**Building age**	Apartment building age at 2020 (year)	8	43	20.85	7.23
	FAR	Floor area ratio: total floor area/site area	0.84	6.99	2.6	0.75
Neighborhood built environment	**GAR**	Neighborhood green area ratio	0.00	0.73	0.11	0.14
	NNRes density	Net density of nighttime nonresidential buildings in neighborhood	0.01	2.15	0.32	0.29

The dependent variable in the second set is a binary variable, named change indicator. It measures whether the household electricity use change is significant in either trend or level variable in the first set, representing gradual and abrupt change, respectively. Its independent variables contain previous household electricity use, household characteristics, and built environment in apartments and neighborhoods (Table 1). The neighborhood is defined as the surrounding area within a 500 m radius from each apartment boundary, which is typically considered a walkable distance. The selection of net density of nonresidential buildings for nighttime use was based on the study by Sung, Lee [9].

2.3 Methods

Two statistical models, namely, ITS analysis and logistic regression, were used in this study. ITS analysis is applied to estimate effects of one or more discrete interventions on time series data [10]. This study utilized the ARIMA model for ITS analysis because of its effectiveness in estimating time-varying trends [10]. Logistic regression is commonly used to predict binary response variable from a set of explanatory variables.

This study applied these models in two steps. ITS analysis was conducted in the first step to test the significance of monthly electricity use change after the new PT with the first dataset. The *auto_arima* function in the Python library *pmdarima* was used to implement the ARIMA model with automatic hyperparameter optimization and selection. In total, 402 models were run for all sample apartments, each having 107 observations. The relationship between the change indicator and independent variables was examined in the second step using logistic regression with the second dataset. The *logit* function in the Python library *statsmodels* was used to implement the logistic regression. Moran's I algorithm was utilized to test residuals, and no significant spatial autocorrelation was found in the model.

3. RESULTS AND DISCUSSIONS

ITS analysis in the first step suggested that 190 apartments demonstrated significant changes in the form of increasing after the new PT (Figure 1).

The results from logistic regression in the second step are summarized in Table 2. The previous electricity use demonstrated a significant inverse relationship with the change indicator: holding other variables constant, one kWh increase in previous monthly household electricity use reduces the odd of change by 0.2%. This is possibly because households that consume additional electricity tend to fulfill their electricity demand properly despite the high cost, and the reduced price in the new PT exhibited a minimal impact on their electricity use behavior with other factors controlled.

Among the household characteristics, floor area per household, housing price, adult female ratio, and elderly ratio demonstrated no significant correlation with the change indicator. Only the adult male ratio exhibited a significant and direct relationship: holding other variables constant, 1% increase of male adult ratio increases the odd of change by 0.05%. This result indicates that male adults tend to change their behavior and consume more electricity when the price lowers whereas female adults and the elderly in Seoul are less sensitive to price changes because of their energy-saving preference. Although the influence of income has been a focus in the literature, this study was not able to examine this influence directly because of the lack of detailed income information. The insignificance of the relationship between housing price and the change indicator may provide hints on this aspect because the housing price is typically used as the approximation of income. However, caution should be taken when using the housing price as an indicator of income due to the limitation of the approximation.

Building age at the apartment level demonstrated no significant influence on the change indicator, while FAR exhibited a significant and direct relationship with the change indicator. Specifically, holding other variables constant, increase of FAR by one increases the odd of change by 8.3%. The latter finding may be explained from two aspects. First, apartments with high FAR are typically newly built with additional built-in appliances that require increased electricity demand and their improved insulation property provides enhanced performance given the same amount of electricity use. These factors may encourage increased energy use when costs decrease. Second, residents living in high-rise buildings are less likely to go outside compared with low-rise building dwellers due to the less enjoyable and longer vertical transportation. As a result, residents in high-rise apartments with high FAR tend to stay at home and use additional electricity to meet their large demand for indoor activities when the price decreases.

Neighborhood-scale variables, green area ratio, and net density of nonresidential buildings for nighttime use failed to demonstrate a significant effect on the change indicator. This result suggested that energy cost exerts a minimal influence on people's outdoor activities. However, daily observations suggested that some low-income and elderly people in Seoul tend to stay outdoors with a comfortable environment to save on energy cost. Therefore, walkable and vibrant neighborhoods provide additional opportunities for outdoor activities to save on indoor energy use and may lead to significant changes in indoor time and electricity use when the price decreases. While findings on this hypothesis showed no significant results, they were inconclusive due to the limited socioeconomic data available. Fine-grained data are necessary for further explorations on this hypothesis.

Table 2. Summary of logistic regression results.

Variable	Coef.	Std.Err.	z	p-value
HH electricity	-0.002	0.001	-2.431	0.015**
HH area	0.006	0.006	1.102	0.270
Housing price	0.027	0.043	0.644	0.520
Male ratio	6.714	3.380	1.986	0.047**
Female ratio	7.181	4.784	1.501	0.133
Elderly ratio	0.620	3.608	0.172	0.864
building age	0.009	0.016	0.537	0.591
FAR	0.306	0.175	1.749	0.080*
GAR	0.577	0.819	0.704	0.481
NNRes density	-0.127	0.389	-0.326	0.744
constant	-6.106	2.832	-2.156	0.031**

Note: ** p<=0.05; * p<=0.1.

4. CONCLUSIONS

This study examines how the new PT implemented in 2017 influenced residential electricity use of different apartments in Seoul. Previous studies on the influence of PT had limitations in neglecting built environment factors due to the lack of data and assuming too simplified process of electricity use behavior changes. This study developed a combined dataset from both big data from multiple sources and urban geospatial data, containing information about households, apartments, and neighborhoods. Two-step analysis was applied in this work. The significance of either gradual or abrupt electricity use change was estimated in the first step using ITS, which considers the complex adaption process of household electricity use behavior. The resulted change indicator was defined in the second step as the dependent variable and its relationship with previous energy use, socioeconomic status, and built environment variables was examined via logistic regression. The results suggested low previous electricity use, high adult male ratio, and high apartment density tend to have significant changes in household electricity use after the new PT. Housing price and built environment factors in neighborhood, which are supposed to influence the electricity use behavior, demonstrated no significant effect on household electricity use with limited evidence.

The results from this study provide a better understanding of the general effect of the new PT on household electricity use in Seoul apartments, which can help policy makers in further evaluating the new policy and creating strategies toward comprehensive sustainability goals, including social welfare, urban energy, and economic development.

While the combined dataset provided extended information for the analysis, it has a main limitation: the combined data are coarse-grained because of different scales in data from multiple sources, which may cause ecological fallacy in analysis. Better data integration method, combination with survey data, and multilevel model will be explored in the future to address this issue.

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