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Population Density and Efficiency in Energy Consumption: An empirical analysis of service establishments[*]

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Abstract

The achievement of both sustainable economic growth and reductions in CO_2 emissions has been an important policy agenda in recent years. This study, using novel establishment-level microdata from the *Energy Consumption Statistics*, empirically analyzes the effect of urban density on energy intensity in the service sector. According to the analysis, the efficiency of energy consumption in service establishments is higher for densely populated cities. Quantitatively, after controlling for differences among industries, energy efficiency increases by approximately 12% when the density in a municipality population doubles. This result suggests that, given a structural transformation toward the service economy, deregulation of excessive restrictions hindering urban agglomeration, and investment in infrastructure in city centers would contribute to environmentally friendly economic growth.

Keywords: service industry, energy efficiency, population density, and productivity.
JEL Classification: L80; Q41; R32

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1. Introduction

The achievement of both sustainable economic growth and a reduction in CO_2 emissions has been an important policy agenda in recent years. This study, using novel establishment-level microdata from the *Energy Consumption Statistics* for the years 2007 and 2008, empirically analyzes the effect of urban density on energy intensity in the service sector.

Under the Kyoto Protocol, Japan is obligated to reduce greenhouse gas (GHG) emissions by 6% between 2008 and 2012 compared to the reference year (1990). To achieve this goal, various policy measures, including promotion of green innovations, diffusion of renewable energy, promotion of modal shifts in transportation, development and diffusion of energy-efficient electrical appliances, introduction of a smart-grid system, and construction of smart communities, have been implemented or planned. The accident at the Fukushima Dai-ichi nuclear power station highlighted the need for further energy savings.

Greenhouse gas emissions in Japan totaled 1,282 billion tons in 2008, which was 1.6% more than the reference year of 1990 (Ministry of the Environment). Energy-related CO_2 emissions accounted for 88.8% of the total greenhouse gas emissions. By sector, although CO_2 emissions from the industrial sector, mainly manufacturing plants, decreased by 13.2% compared to 1990, those from the transportation sector, commercial sector, and residential sector increased 8.3%, 43.0%, and 34.2%, respectively. Due to the increase in information technology equipment, the expansion of floor space, and the trend toward a service economy, CO_2 emissions from the commercial sector, where service establishments account for a large proportion, are increasing rapidly.[1] The proportion of the service industry in the total energy consumption increased from 13.5% in 1990 to 18.8% in 2008 (Table 1). The increase in the GDP share of the service industry has contributed to its proportion of energy consumption, but the deterioration of this industry's energy consumption per output is also an important factor. From 1990 to 2008, energy consumption per unit of real GDP improved by 14.2% in the manufacturing industry

[1] In most energy statistics, "industrial sector" includes manufacturing, agriculture, forestry, and fishing, mining, and construction. "Commercial sector" includes office buildings, department stores, wholesale and retail, restaurants, schools, hotels, hospitals, theater, and other services. The transport industry is classified in the "transportation sector." In the transportation sector, CO_2 emissions from private vehicles increased substantially; there was a 35.6% increase compared to the reference year.

but deteriorated by 8.5% in the service industry.

According to published data from the *Energy Consumption Statistics* (Ministry of Economy, Trade and Industry) in 2008, energy-intensive service industries include “laundry, beauty salons, barbers, and bathhouses,” “hotels,” “restaurants,” “nursing homes,” and “health care” (Table 2). Some service industries exhibit higher energy intensities than the average manufacturing industry.[2]

Given the present trend toward a service economy, improving the productivity of the service industry has become an important policy agenda in major advanced countries. However, as productivity studies for the service industry have been notoriously scarce, strong efforts in this field are required and expected. Recent economic theories on productivity emphasize firm-level heterogeneity, and empirical studies have confirmed large dispersions of productivity among firms or establishments, even in a narrowly defined industry (Bloom and Van Reenen, 2010; Syverson, 2011).[3] Although productivity studies on the service industry using microdata have been limited, pioneering studies have found that the dispersion of productivity is larger in the service industry than in the manufacturing industry (Oulton, 1998; Faggio et al., 2007; Morikawa, 2007). This finding suggests that the dispersion of energy efficiency may be extensive among service establishments. Analysis of the determinants of energy efficiency for the service industry at the establishment level will contribute to the planning of policy measures to improve the energy efficiency of this sector.

Simultaneous production and consumption is frequently identified as a distinct characteristic of the service industry. As a result, the demand density of a particular location affects the productivity of this industry. Morikawa (2011) found significant economies of density, wherein total factor productivity (TFP) of service establishments increases by 7–15% when the municipality population density doubles. The present study empirically analyzes the economies of density and its determinants from the viewpoint of energy efficiency.

As we survey in the next section, many studies have been conducted on the relationship between urban density and energy consumption, but most studies have focused on the

[2] In this table, the figure for the manufacturing industry is the sample average from the *Energy Consumption Statistics*, which does not cover the energy consumption of large plants that belong to the nine energy-intensive manufacturing industries.
[3] Bloom et al. (2010), based on data for manufacturing establishments in the UK, indicate that establishments in firms that are better managed are significantly less energy intensive and that the effect is quantitatively large.

transportation or household sectors. Analysis of the energy consumption of service establishments using microdata has rarely been conducted. Under these circumstances, the *Energy Consumption Statistics,* initiated by the Ministry of Economy, Trade and Industry in 2007, which comprehensively covers service industries, is extremely useful for analyzing energy consumption. The aim of this study is to provide information on this important topic by making use of newly available microdata from the *Energy Consumption Statistics*.

According to the findings in this study, the energy usage of the service establishments is more efficient in densely populated cities after accounting for the difference in industry composition. Quantitatively, energy consumption per output decreases by approximately 12% (i.e., 12% more efficient) when the city population density doubles. Most of this efficiency can be accounted for by the different usage of floor space, labor productivity, and climate conditions. Particularly because of high land prices and office rents, efficient use of floor space in densely populated cities contributes to the conservation of energy in service establishments.

This paper is structured as follows. Section 2 briefly reviews relevant studies on the relationship between economic density and energy consumption or CO_2 emissions. Section 3 explains the method of analysis and the data used. Section 4 reports and interprets the results, and Section 5 concludes with policy implications.

2. Literature Review

A large number of studies have investigated the relationship between urban density and energy consumption. Newman and Kenworthy (1989), a pioneering study, pointed out the negative correlation between urban density and gasoline consumption using cross sectional data from 32 large cities around the world in 1980. Karathodorou et al. (2010) estimated a fuel demand model for 84 urban areas around the world in 1995 to provide an estimate of the elasticity of demand with respect to urban density. They report that the elasticities of car ownership, annual distance driven, and fuel consumption per km with respect to urban density are all statistically significant (-0.12, -0.24, and -0.35, respectively).

Bento et al. (2005) also focused on the use of motor vehicles. Using data for 114 U.S. urban areas in 1990, they analyzed the effects of urban configurations and public transportation on the choice of commuting mode and annual vehicle miles traveled (VMT) of households. They found that the probability of driving to work is lower with a higher population centrality and that population centrality has a significant effect on annual household VMT. Brownstone and Golob (2009) performed an empirical study on the relationships among residential density, vehicle use, and fuel consumption in the U.S. By estimating a joint model of residential density, vehicle use, and fuel consumption, they accounted for the endogenous selection of residential location. According to their analysis on California households, a lower density of 1,000 housing units per square mile (40% of the sample average) implies an increase of 4.8% more miles driven per year and 5.5% more gallons of fuel consumption per household. Su (2011), using cross-sections of U.S. household data, estimated the elasticity of gasoline consumption to population density to be -0.064 after controlling for household characteristics, freeway road density, and congestion. These studies confirm the empirical relationship between the density of urban areas and vehicle energy use.

Glaeser and Kahn (2010) extended the analysis on the relationship between the spatial distribution of populations and CO_2 emissions to home heating and electricity usage. By employing U.S. household-level data, they analyzed CO_2 emissions associated with gasoline consumption, public transportation, home heating and electricity usage. They found that central cities have significantly lower emissions than suburban areas and that there is a strong negative association between emissions and land use regulations. They argue that by restricting new development, the cleanest areas of the country would be pushing new development toward places with higher emissions. Kahn (2010) performed an empirical analysis on the relationship between the geographical location of economic activity and CO_2 emissions from households in the U.S. This study confirms a negative association between central city living and a household's carbon footprint and suggests policies to improve the quality of life and local public goods in city centers, including reducing inner-city crime and improving urban public schools, which would be beneficial in reducing greenhouse gas emissions.

To summarize, energy consumption and CO_2 emissions are lower in denser cities. However, previous studies have been confined to the gasoline consumption of vehicles or the energy usage of households. Studies on the commercial sector, including retail and service industries, are scarce.

3. Data and Methodology

The *Energy Consumption Statistics*, collected by the Ministry of Economy, Trade and Industry and used in this study, is a new set of official statistics that was started in 2007. The purpose of the annual statistics is to collect detailed information on the energy usage of industrial and commercial sectors. Datasets for the years 2007 and 2008 were available at the time of this study. Information on the energy consumption of large plants that belong to nine energy-intensive manufacturing industries, including iron and steel, chemical, and paper and pulp, have been collected by the *Survey of Energy Consumption in the Selected Industries* since 1981. However, the service industry, which is classified as part of the commercial sector, was not covered by this survey. Under increasing pressure to reduce greenhouse gas emissions, the Japanese government started the new statistical collection to obtain detailed data on energy consumption at establishment level and to plan effective energy conservation policies. The following establishments are covered by the *Energy Consumption Statistics*: 1) small- and medium-sized plants in the nine energy-intensive manufacturing industries; 2) establishments of other manufacturing industries; 3) establishments of agriculture, mining, and construction; and 4) establishments of commerce and service industries. Approximately 200,000 establishments are covered. The survey items include electricity consumption, fuel (e.g., gas, kerosene, heavy oil, gasoline) consumption, self-generation of electricity, consumption of heat energy (steam and hot water), number of employees, floor space (m^2), and annual sales.

Because the focus of this study is to determine the energy efficiency of the service industry, we restricted the sample establishments belonging to the tertiary sector, except for the electricity, gas and heating supply industries and the transportation industry. The numbers of sampled establishments are approximately 66,000 in 2007 and 58,000 in 2008.[4] However, the final sample is smaller than these figures because data on annual sales or floor space, which are necessary for the analysis, were missing for several establishments. The

[4] The analysis in this study uses a dataset provided by the Agency of Natural Resources and Energy under the permission from the Agency. Several data cleaning procedures, including the allocation of energy in a building into different tenants, the removal of outliers, and the conversion to the single energy unit (GJ) were conducted in the Agency. This study treats these data cleaning procedures as given.

specific survey items used in this study are total annual energy consumption (GJ), number of employees, floor space (m^2), annual sales, three-digit industry classification code, and city code. City-level data on population and land area (excluding forests and lakes) were taken from published information of the Statistical Bureau, Ministry of Internal Affairs and Communications and were merged with the data of the *Energy Consumption Statistics*. Because data for 2007 and 2008 are available, the data for these two years were pooled in the analysis. [5]

Because the main interest of this study is the relationship between density and energy efficiency of service establishments, the natural log of the energy consumption per sales (GJ/10 thousand yen) was used as the measure of energy efficiency (*lnenergy_sale*). Smaller figures indicate higher energy efficiency. The method of analysis was a simple pooled OLS regression, where the log of the city population density (*lnpopdens*) was used as the main explanatory variable to explain energy efficiency. The estimated coefficients for population density can be interpreted as the elasticity. The negative coefficient of this variable means that establishments located in dense cities are more energy efficient. The denominator for the calculation of population density is the land area (km^2), excluding forests and lakes. In addition to the baseline estimation, we also used daytime population and the number of workers as numerators in calculating the density (*lnpopdens_day, lnworkdens*) to check the robustness of the results.

Additional explanatory (control) variables are the three-digit industry dummies, year dummy 2008 (*yeardum*), natural log of the floor space per sale (m^2/10 thousand yen: *lnfloor_sale*), natural log of the number of employees per sale (employees/10 thousand yen: *lnemp_sale*), heating degree days of the year (*hdd*), and cooling degree days of the year (*cdd*). Among these variables, the floor space and number of employees were measures of representative inputs available in the dataset, which are proxies for capital and labor. Because the annual sales were used as the denominator of the dependent variable (*lnenergy_sale*), both of these explanatory variables representing input were normalized and expressed as units per sale. That is, these variables are the inverse of the single-factor productivity measures. When the estimated coefficients of these variables are positive, the result can be interpreted as indicating a positive relationship between land or labor productivity and energy efficiency. Heating and cooling degree days (*hdd, cdd*) were used to control for the effects of different

[5] The Energy Consumption Survey is not designed to construct panel data.

regional climate conditions on energy usage. These variables are at the prefecture level because they were not available at the city level. The calculation of heating degree days is as follows. First, the average temperature on any given day was subtracted from the base temperature (14 degrees Celsius). Then, these figures were summed up throughout the year. To calculate the cooling degree days, the average temperature of a day exceeding 24 degrees Celsius was taken, and 22 degrees Celsius was subtracted from it. These figures were summed up throughout the year. These degree days are known to be related to the energy consumption of households. [6] We collected daily temperature data at the prefecture capitals from the Japan Meteorological Agency (JMA) website and calculated the degree days for the years 2007 and 2008. The prefecture with the highest heating degree days was Hokkaido, and the lowest was Okinawa. The reverse is true for the cooling degree days. The equation to be estimated is shown below. Table 3 indicates the summary statistics of the variables.[7]

$$\text{lnenergy\_sale} = ß_0 + ß_1 \text{ lnpopdens} + ß_2 \text{ lnfloor\_sale} + ß_3 \text{ lnemp\_sale} + ß_4 \text{ hdd} + ß_5 \text{ cdd} + ß_6 \text{ yeardum} + ß_d \Sigma \text{ industry dummies} + u_i \quad [1]$$

4. Estimation Results

Before presenting the regression results, we calculated simple statistics (mean, standard deviation, median, 10th percentile, and 90th percentile) on the distribution of the energy efficiency at the establishment level (Table 4). The 10th and the 90th percentile figures (p10, p90) of the measure of energy efficiency (log of GJ/10 thousand yen) are 0.0015 and 0.2140; therefore, there was large dispersion among establishments.

The regression results are shown in Table 5. When using only the population density and year dummy, the estimated elasticity of energy efficiency with respect to population density was fairly large (approximately -0.39), but the figure drops approximately 50% (-0.19) when three-digit industry dummies were added (column (1), (2)). This result suggests that relatively energy intensive service industries tend to be located in less populated regions.

6 Metcalf and Hassett (1999) and Reiss and White (2008), for example, use heating and cooling degree days in analyzing energy consumption of residences.

7 In the dataset for 2008, the energy consumption of one establishment is extremely large, and the figure is obviously an outlier. We removed this establishment from the sample.

However, even after controlling for the different industry composition, the quantitative magnitude of the elasticity of -0.19 was not small: energy efficiency improves by 12% when the population density of the city doubles.

The inefficient use of energy in low-density regions may be the result of a rational decision to make the best use of relatively inexpensive land or floor space intensively. As a result, such establishments may consume more energy for heating/cooling and lighting. In addition, labor-intensive production may require more energy per output. To control for these effects, we added explanatory variables representing capital and labor inputs, as explained previously. The coefficient of floor space is large (approximately 0.54), indicating that the larger the floor space, the greater the energy consumption (Table 5, column (3)). The coefficient for the number of employees is approximately 0.35. This result means that less productive establishments use energy inefficiently. After controlling for these effects, the coefficient of the population density remained negative and highly significant, but its value substantially decreased to approximately -0.04. This finding means that energy efficiency at the establishment level is approximately 3% higher when the population density of the city doubles. Furthermore, the difference in climate conditions may affect energy efficiency. If densely populated large cities are located in places with mild climates, then the effect of population density may be overstated. Although the coefficient for cooling degree days was insignificant, the coefficient for heating degree days was positive and highly significant (Table 5, column (4)). With other factors remaining constant, service establishments that are located in cold regions tended to consume more energy. Even controlling for these factors, the coefficient of density remained negative and significant, but the value dropped to -0.016.[8]

Based on the regression results, we decomposed the difference in energy efficiency between the average of large cities (designated cities by the government ordinance) and the average of other (small) cities into the contributions of various factors. The "explained" component is simply calculated with a widely used version of the Oaxaca-Blinder type decomposition.

$$y^l - y^s = (X^l - X^s)*\beta \quad [2]$$

[8] When estimations were made separately for 2007 and 2008, the values of the estimated coefficients were essentially the same as for the results using pooled data.

where y^l and y^s are the average energy consumption per sales for large cities and other (small) cities, X^l and X^s are the average of the explanatory variables for both types of cities, and β is the estimated coefficient.

According to this calculation, floor space has the strongest contribution (approximately 37%), labor and climate both contribute approximately 12%, and the contribution of the pure population density factor is approximately 3% (Table 6).[9]

The above estimations used log population density as a main explanatory variable. To check the robustness of these estimations, we used the daytime population density (*lnpopdens_day*) and worker density (*lnworkdens*) as explanatory variables. Table 7 shows the estimated elasticities of energy use with respect to these alternative density variables. The figures are somewhat larger than the results using simple (night) population density, but the conclusion is fundamentally unchanged.

The results of the analysis can be summarized as follows.

(1) Energy usage of service establishments is more efficient in densely populated cities. After accounting for the difference in industry composition, the energy consumption per output is approximately 12% lower when population density doubles.

(2) Approximately half of the density effects can be explained by the difference in factor productivity, especially by the difference in land use efficiency.

(3) Decreased use of energy for heating also contributes to energy efficiency in densely populated large cities that are located in mild climates.

5. Conclusion

In response to the policy interest in achieving both sustainable economic growth and reductions in CO_2 emissions, this study, using establishment-level microdata from the *Energy Consumption Statistics*, empirically analyzed the effect of urban density on energy intensity in the service sector. The statistical data were recently made available and are potentially very valuable in analyzing the energy usage of many types of industries.

Energy consumption has been decreasing in the manufacturing sector through various efforts to conserve energy, but energy consumption of the commercial, transportation and residential sectors has been increasing continuously. Several U.S. studies have indicated that CO_2 emissions from vehicles and residences are lower in dense regions, but studies on the service sector have been limited.

According to the present analysis, there is a statistically significant relationship between energy consumption efficiency of service establishments and population density: the efficiency of energy consumption in service establishments is higher in densely populated cities. Quantitatively, after controlling for the differences in industry structure, energy efficiency improves by approximately 12% when the density in a municipality population doubles. A large proportion of this figure can be explained by the difference in the intensity of floor space use, but differences in the labor productivity and climate conditions are also contributing factors. These results indicate that the efficient use of energy in large and dense cities is mainly driven by higher factor productivity.

The results of this study suggest that given a structural transformation toward the service economy, deregulation of excessive restrictions hindering urban agglomeration, investment in infrastructure in city centers, and construction of compact cities would contribute to environmentally friendly economic growth. On the other hand, if the spatial distribution of populations or economic activities is regarded as a given condition, then expansion of sources of clean energy, such as solar, wind, small- and medium-sized hydroelectric plants, and geothermal energy, in rural areas would also contribute to a nationwide reduction in CO_2 emissions. Individual firms and establishments are choosing their locations rationally based on the relative factor prices of energy, land, and wages; thus, the inefficiency of energy use in rural regions does not necessarily mean a normative evaluation that the input mix is socially undesirable.

Because the present analysis is cross-sectional, we caution that the endogeneity bias arising from establishments' location choices is not controlled. Even in a narrowly defined industry, establishments with low energy efficiency may choose to be located in rural regions. In addition, it should be noted that the measure of energy consumption in this study is the final energy consumption of the establishments, which is different from primary energy consumption, including the loss of energy in the generation and transmission of electricity.

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[9] The unexplained residual includes the effects of different industry compositions.

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Table 1 Service Industry Proportion of Total Energy Consumption

1990	2000	2008
13.5%	15.8%	18.8%

(Notes) Calculated from the *Energy Supply and Demand* (Ministry of Economy, Trade and Industry). The service industry does not include electricity and gas or transportation.

Table 2 Service Industries with High Energy Intensities

Industries	Energy consumption/sales (GJ/million yen)
Waste disposal	31.74
Laundry, beauty salons, barbers, and bathhouses	27.45
Hotels	23.45
Other services	22.05
Other education services	18.06
Catering	15.07
Restaurants	10.99
Nursing homes	9.27
Health care	4.62
School education	4.39
(Manufacturing average)	5.73

(Source) Energy Consumption Statistics (2008).

Table 3 Summary Statistics

Variable		Obs	Mean	Std. Dev.	Min	Max
energy	(TJ)	52,107	84	11,970	0.00002	2,699,257
emp		51,911	122	483	1	67,525
floor	(m^2)	50,210	7,022	35,016	2	2,564,080
sale		52,107	6,534	64,416	1	5,625,481
lnenergy_sale	(GJ/10 thousands yen)	52,107	5.426	2.048	-6.300	17.879
lnfloor_sale	(m^2/10 thousands yen)	50,210	5.379	1.759	-4.983	15.025
lnemp_sale	(per 10 thousands yen)	51,911	1.909	1.355	-7.157	10.069
lnpopdens		49,816	7.821	1.194	2.996	9.900
lnpopdens_day		49,816	7.931	1.391	3.014	11.203
lnworkdens		49,816	7.085	1.174	2.388	9.107
hdd		52,107	1023.4	453.2	2.1	2528.9
cdd		52,107	384.1	160.7	16.3	1021.1

(Notes) The figures are pooled data for the years 2007 and 2008. The establishments for which energy consumption, annual sales or floor space are missing are excluded.

Table 4 Distribution of Energy Consumption per Sale

	N	mean	sd	p10	p50	p90
energy_sale	52,107	0.5211	34.0473	0.0015	0.0320	0.2140

(Notes) The figures are pooled data for the years 2007 and 2008. The establishments for which energy consumption, annual sales or floor space are missing are excluded.

Table 5 Regression Results of Population Density and Energy Efficiency

	(1)		(2)		(3)		(4)	
lnpopdens	-0.3933	***	-0.1886	***	-0.0423	***	-0.0157	***
	(-52.48)		(-30.67)		(-9.22)		(-3.18)	
lnfloor_sale					0.5431	***	0.5419	***
					(111.50)		(111.43)	
lnemp_sale					0.3531	***	0.3554	***
					(58.74)		(59.24)	
hdd							0.0002	***
							(7.78)	
cdd							0.0000	
							(0.58)	
cons.	8.5365	***	6.9351	***	2.2005	***	1.7814	***
	(142.54)		(141.70)		(49.17)		(24.51)	
Industry dummies	no		yes		yes		yes	
year dummy (2008)	yes		yes		yes		yes	
Number of obs.	49,816		49,816		47,846		47,846	
Adjusted R^2	0.0527		0.4574		0.7170		0.7182	

(Note) OLS estimates with t-values in parentheses. * significant at 10%; ** significant at 5%; *** significant at 1%.

Table 6 Contributions of the Factors Determining the Difference in Energy Efficiency between Large Cities and Other Cities

Determinants	Contribution
Floor space	36.5%
Number of employees	12.3%
Climate	12.1%
Pure population density effect	3.0%

(Note) The contributions are calculated from the regression results. Fourteen large cities are designated by the government ordinance.

Table 7 Estimation Results Using Alternative Density Measures

	(1) Without controls	(2) With industry dummies	(3) With all controls
(1) Population density	-0.393	-0.189	-0.016
(2) Daytime population density	-0.419	-0.204	-0.022
(3) Worker density	-0.402	-0.192	-0.016

(Note) Estimates from pooled data. The values are the coefficients for density.