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An analysis of the influence of urban form on energy consumption by individual consumption behaviors from a microeconomic viewpoint

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HIGHLIGHTS

- Energy consumption is estimated by demand of composite goods, mobility goods.
- 52.84 GJ of energy is estimated to satisfy one person per year in Kumamoto.
- 80% of energy is for composite goods and 20% for mobility goods.
- Land use diversity and distance to city center, affect energy consumption most.
- Employment density and transit fare are influential factors of energy efficiency.

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ABSTRACT

Using 1997 personal trip survey (PTS) data in the Kumamoto metropolitan area, this paper examined the influence of urban form on energy consumption through an energy estimation model from a microeconomic perspective. As all goods and service are assumed to satisfy the need of people, we estimated the individual energy consumption based on the demand of goods, which is explained by a utility maximization problem constrained by income. 52.84 GJ of energy is estimated for one person one year in Kumamoto metropolitan area. 19.57% of energy is used for mobility goods. A spatial regression was performed to analyze the relationship between energy efficiency and urban form characteristics in terms of density, diversity, and accessibility. The results of regression analysis show that employment density, ratio of employee in retail department, transit fare, and distance to city center are the most influential factors of energy efficiency. Findings suggest compact development and integrated policies for increasing employment density, especially, employment proportion of local residents are suggested. Moreover, measures to improve the attractiveness of mass transit should be encouraged to increase energy efficiency in Kumamoto.

1. Introduction

Urbanization is occurring at an accelerating pace, accompanied with the creation of some megacities, which is currently defined by the United Nation as cities with more than 10 million population (Bugliarello, 2006). The magnitude and rate of urban growth make urban sustainable development become a crucial matter of global sustainability. Many studies have discussed that the urban forms attribute to sustainable urban development, such as the compact city (Frey, 1999; Williams et al., 2000; Jabareen, 2006). Urban from is considered to be an important factor in addressing urban sustainable development and climate change. The spatial configuration of urban land use within a metropolitan area resulted in diverse social, ecological, and environmental consequences (Camagni et al., 2002; Holden, 2004). These consequences of urban form have been analyzed by energy consumption because of two reasons. First, from the physical standpoint, the urban spatial configuration and land use affect the total amount of energy consumption. Second, the density and intensity of activities, such as traffic and industry, is a major factor influencing energy consumption. Moreover, growing concerns about surging oil prices and the greenhouse gas produced by burning fossil fuels require that urban development not only minimizes resource use and spatial displacement for ecosystems, but also improves energy efficiency.

The debate regarding the relationship between energy consumption and urban form have attracted lots of studies from

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both theoretical and empirical aspects. Some literatures analyzed the relationship between energy consumption and urban form factors among cities. Aggregate studies examined the bivariate relationship between urban form and energy consumption (Crane, 2000; Ewing and Cervero, 2010). Newman and Kenworthy (1999) analyzed the relationship between population density and gasoline consumption in megacities worldwide, which suggested an obvious negative relationship between population density and transportation energy consumption per capita. Their analysis did not consider socioeconomic variations among cities. Such an analysis fails to emphasize the social and economic effects on energy consumption.

Socioeconomic attributes are very influential to household travel and energy consumption (Susilo and Stead, 2008; Musti et al., 2010; Liu and Shen, 2011). Increasing the income leads to a change in consumer needs, which results in rising energy consumption due to growing numbers of household electrical appliances and shifting toward energy intensive transportation modes (Feng et al., 2010). Previous studies utilized disaggregate household data to investigate the differences of household energy consumption in different urban living environment. Using the data of 2001 National Household Travel Survey, Brownstone and Golob (2009) analyzed the relationship of residential density, vehicle use, and fuel consumption for California households. They found the most influential variables were the number of household drivers, the number of workers, education and income. Based on six case studies in the United Kingdom and the Netherlands, Banister et al. (1997) found factors significantly affecting urban energy consumption were density, employment, and car ownership. This kind of disaggregate studies included a rich set of socioeconomic variables and clearly demonstrated the effects of urban form on energy consumption. However, most studies focused on household, and the data included only household energy consumption in Residential and Transportation sectors, such as energy for space heating and cooling, appliances and lighting, domestic hot water and private cars. Energy consumption for Commercial and public services, which shared largely in household energy consumption, was not considered. According to a statistic report from Agency for Natural Resources and Energy, METI (Ministry of Economy, Trade and Industry), energy use in Commercial sector accounts for 25.07% of total energy consumption in all sectors in Kumamoto prefecture, 1997, compared to that of 23.07% in Residential sector. A study in China demonstrated the decreased absolute amount of energy consumption and CO_2 emissions for making food, but growth for education, cultural and recreational services as income increased (Feng et al., 2010).

It is essential but difficult to obtain household energy data of all sectors. The way to solve this problem is to build models to estimate the household energy consumption. Models that describe behaviors under a number of demographic conditions enable us to estimate energy consumption and assess the impact of urban form on energy use. One commonly applied model was to forecast urban energy consumption in transportation sector over a range of driving conditions (Stone et al., 2007; Swana et al., 2011). We previously developed a quantitative model for estimating energy consumption based on individual consumption behaviors (Yin and Mizokami, 2011). The model was applied to assess compact level of cities based on individual energy consumption and utility. Moreover, models that integrated land use, transportation and residential location choice have been built to estimate energy consumption, such as integrated land use and transport model TRANUS (Bravo et al., 2010). TRANUS enables users to study the effects of land use and transport policies, either singly or in combination. The location and interaction of activities determine the demand of energy consumption. Its effort to model the causal mechanisms, which combines direct and indirect links through intermediate variables of urban form to travel and energy consumption, making TRANUS a very attractive point. However, the model requires extensive data for calibration which limits its application.

Anderson et al. (1996) provided a good literature synthesis by reviewing the basic concepts of urban form, the relationships among urban form, energy use, and the effects of using various land use and transportation policy instruments to achieve energy reduction. Although a growing body of literature support the notion that urban form plays a role in energy consumption, the empirical findings on energy consumption and urban form outcomes are less conclusive, and little is known about how urban form influences resident consumption behaviors. They concluded that the influence of urban form on energy consumption is still unclear. This uncertainty therefore requires more empirical work and more comprehensive quantitative models that involved more behavior analysis. So far, few researchers have empirically investigate the linkage between the urban form factors and individual energy consumption by behavior data.

This paper studies the link between urban form and energy consumption through individual consumption behaviors from a microeconomic perspective. At micro level, the effect of urban form on energy consumption is reflected by the individual consumption behaviors. A focus on behavior allows for consideration of influence of socioeconomic factors, such as income. Moreover, focusing on consumption behaviors promotes ways to estimate individual energy use for daily living. It is expected that this estimation approach based on consumption behaviors would be more feasible and rational for a better understanding of the effects of urban form on energy consumption, which will have positive returns for both the environment and city policy making.

Section 2 presents the methodology, including a model for energy estimation, an index of energy efficiency, and the linear regression. Section 3 describes the context of the empirical work, the studied areas of Kumamoto, data set, and quantitative process for energy estimation. Section 4 presents and discusses the energy estimation results and relationship analysis of urban from and energy consumption by a regression model. The main findings and suggestions for policies in Kumamoto are summarized in Section 5.

2. Methodology

2.1. Energy estimation model

The purpose of all urban activities is assumed to satisfy the demand of residents, which need energy to support. Thus, the energy consumption can be estimated based on the demand of individuals. In microeconomics, the demand is represented by the need of goods and service, which are explained by personal consumption behaviors. In economics, utility is a representation of preferences over some set of goods and services. Although it is impossible to measure the utility derived from a good or service, it is usually possible to rank the alternatives in their order of preference to the consumer. Economists have theorized that a utility function could be used to express the scale of preference to describe consumer behaviors. Individual demand is mathematically modeled as the process of maximizing utility under given constraints, such as income (Stigler, 1950).

This study focuses on the individual final energy consumption of some categories that closely relate to the daily living, including energy use in Residential, Commercial, and Transportation sectors. Energy in Industry sector is not considered in this study because it has less direct influence on individual daily life compared to the other three sectors. Moreover, it is complex and not suitable to