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Energy Consumption and Quality of Life: Energy Efficiency Index

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Abstract

This paper shows a micro-economic based quantitative analysis scheme to evaluate the energy efficiency of cities based on quality of life and energy consumption. By representing the quality of life by utility, this study developed a CES-based model to estimate the individual demand of non-mobility goods, car trips, and public transport trips at the maximum utility level. Energy consumption is estimated by the demand of goods. An energy efficiency index is developed to show the relative energy consumption on the certain quality of life. We applied this model to Nagasaki region. Higher energy efficiency zones were found in city center and along the mass transit lines. Such findings suggest that a compact urban structure and higher public transport accessibility could increase energy efficiency.

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Keywords: Energy consumption; Quality of life; Consumption behavior; Energy efficiency

1. Introduction

Sustainable urban development has being a crucial element affecting the long-term outlook of humanity [1][2]. Growing concerns about urging oil prices and greenhouse gases produced by burning fossil fuels require the urban development to minimize the use of resources, spatial displacement of environment and improve energy efficiency [3][4][5]. Energy consumption by urban activities has often

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become a major concern. The intensity of activities, such as traffic and industry, are seen as major factors influencing energy consumption. Energy consumption is strongly related to actual land use and transportation as well as population density. Urban activities like production and consumption have been supported by consumption behaviors and transportation service which distribute goods [6].

Various kinds of consumption behavior also affect the achievement of quality level of life. More consumption of goods is believed closely related to the quality of life. It would influence the quality of life of individuals if we aim to reduce energy consumption through consumption behaviors. It is usually believed that reduced energy consumption means decreasing the quality level of life. Few studies focus on the goal of energy consumption reduction meanwhile considers the quality of life. It is important to consider the quality of life when we make policy aiming for reducing energy consumption [7].

This paper aims to introduce energy efficiency as a new index to evaluate the relative achievement of energy reduction. This index considers both energy consumption and quality of life. A model is built to estimate the energy consumption based on consumption of goods for present quality of life. We also apply the model into Nagasaki region to explore the energy efficiency of zones.

2. Method

2.1. Subsidy, cost, and revenue

All consumption behaviors of residents are classified as consumption behaviors for non-mobility goods and mobility goods. Mobility goods include car trips and public transport trips. Non-mobility goods are defined as all other goods except mobility goods. Specially, non-mobility goods include goods in the Residential and Commercial sectors, such as heating, cooling, food and recreation. Following assumptions are essential parts for the approach to estimate demand of goods: a) A resident is assumed to consume two types of goods: non-mobility goods and mobility goods. b) The demand of mobility goods is a function of car trips and public transport trips. c) Individuals are supposed to achieve maximum utility and maximum mobility at same time. d) All income is spent on consuming without saving. e) Present level of quality of life is expressed by the maximum utility.

2.2. Quality of life and utility

Quality of life is the general well-being of individuals and societies. There are many indexes to quantify it. Utility is one of them from microeconomic viewpoint. People are supposed to achieve the well-being by consumption of goods. In microeconomics, utility represents satisfaction experienced by the consumer of a good [4]. People are assumed to make decisions based on their preferences over different goods, the cost of goods, and the budget constraints (income) to maximize the utility[8].

A two order Constant Elasticity of Substitution (CES) function are applied to express the relationship between utility, mobility, and demand of goods (Eq. (1) and Eq. (2)).

$$u_i(x_{1i}, x_{2i}) = \left\{\alpha_1 x_{1i}^{(\sigma_1-1)/\sigma_1} + \alpha_2 x_{2i}^{(\sigma_1-1)/\sigma_1}\right\}^{\sigma_1/(\sigma-1_1)} \quad (1)$$

$$x_{2i}(x_{2Ci}, x_{2Mi}) = \left\{\alpha_{2C} x_{2Ci}^{(\sigma_2-1)/\sigma_2} + \alpha_{2M} x_{2Mi}^{(\sigma_2-1)/\sigma_2}\right\}^{\sigma_2/(\sigma_2-1)} \quad (2)$$

where u_i indicates utility level. x_{1i}, x_{2i} are demand of non-mobility goods and mobility goods, respectively. x_{2Ci}, x_{2Mi} are demand of car trips and public transport trips, respectively; σ_1 represents substitution elasticity between non-mobility goods and mobility goods; σ_2 is substitution elasticity between car trips and public transport trips; α_1, α_2 are expenditure share of non-mobility goods and mobility goods to income, respectively; α_{2C}, α_{2M} are expenditure share of car trips and public transport trips to traffic budget, respectively.

2.3. Demand of goods

The demand of goods is estimated by solutions of maximization problems of utility and mobility (Eq. (3) and Eq. (4)). In zone i, p_{1i}, p_{2i}, p_{2Ci}, p_{2Mi} represent price of non-mobility goods, mobility goods, car trips, and public transport trips, respectively; Ii is income (person per day); I_{2i} indicates traffic budget (person per day).

$$\max_{x_{1i},x_{2i}} : u_i = \left\{\alpha_1 x_{1i}^{(\sigma_1-1)/\sigma_1} + \alpha_2 x_{2i}^{(\sigma_1-1)/\sigma_1}\right\}^{\sigma_1/(\sigma_1-1)} \quad s.t. \quad p_{1i}x_{1i} + p_{2i}x_{2i} \le I_i \tag{3}$$

$$\max_{x_{2Ci},x_{2Mi}} : x_{2i} = \left\{\alpha_{2C} x_{2Ci}^{(\sigma_2-1)/\sigma_2} + \alpha_{2M} x_{2Mi}^{(\sigma_2-1)/\sigma_2}\right\}^{\sigma_2/(\sigma_2-1)} \quad s.t. \quad p_{2Ci}x_{2Ci} + p_{2Mi}x_{2Mi} \le I_{2i} \tag{4}$$

The solutions of two maximization problems, which are the optimal demand of non-mobility goods x^*_{1i} , demand of car trips x^*_{2Ci} , and the demand of public transport trips x^*_{2Mi} goods, are shown as Eq. (5), Eq. (6), and Eq. (7).

$$x_{1i}^* = \left(\frac{\alpha_1}{p_{1i}}\right)^{\sigma_1} \left\{ \frac{I_i}{\left[\alpha_1^{\sigma_1} p_{1i}^{1-\sigma_1} + \alpha_2^{\sigma_1}\left(\alpha_{2Ci}^{\sigma_2} p_{2Ci}^{(1-\sigma_2)} + \alpha_{2Mi}^{\sigma_2} p_{2Mi}^{(1-\sigma_2)}\right)^{\frac{(1-\sigma_1)}{(1-\sigma_2)}}\right]} \right\} \tag{5}$$

$$x_{2Ci}^* = \left(\frac{\alpha_{2C}}{p_{2Ci}}\right)^{\sigma_2} \alpha_2^{\sigma_1} (\alpha_{2C}^{\sigma_2} p_{2Ci}^{1-\sigma_2} + \alpha_{2M}^{\sigma_2} p_{2Mi}^{1-\sigma_2})^{\left((\sigma_2-\sigma_1)/(1-\sigma_2)\right)} \left\{\alpha_1^{\sigma_1} p_{1i}^{1-\sigma_1} + \alpha_2^{\sigma_1} (\alpha_{2C}^{\sigma_2} p_{2Ci}^{1-\sigma_2} + \alpha_{2M}^{\sigma_2} p_{2Mi}^{1-\sigma_2})^{\left((1-\sigma_1)/(1-\sigma_2)\right)}\right\}^{-1} I_i \tag{6}$$

$$x_{2Mi}^* = \left(\frac{\alpha_{2M}}{p_{2Mi}}\right)^{\sigma_2} \alpha_2^{\sigma_1} (\alpha_{2C}^{\sigma_2} p_{2Ci}^{1-\sigma_2} + \alpha_{2M}^{\sigma_2} p_{2Mi}^{1-\sigma_2})^{\left((\sigma_2-\sigma_1)/(1-\sigma_2)\right)} \left\{\alpha_1^{\sigma_1} p_{1i}^{1-\sigma_1} + \alpha_2^{\sigma_1} (\alpha_{2C}^{\sigma_2} p_{2Ci}^{1-\sigma_2} + \alpha_{2M}^{\sigma_2} p_{2Mi}^{1-\sigma_2})^{\left((1-\sigma_1)/(1-\sigma_2)\right)}\right\}^{-1} I_i \tag{7}$$

2.4. Energy consumption

Individual energy consumption in zone i is calculated based on demand of goods, energy unit, and trip time (Eq. (8)). E_i is the energy consumption of a resident in zone i. x^*_{1i}, x^*_{1Ci}, x^*_{1Mi}, are demand of non-mobility goods, car trips, and mass transit trips on the maximum utility (u^*_i), respectively. e_1, e_2, and e_3, are energy units of non-mobility goods, car trip, and mass transit trip, respectively. Energy units are used to evaluate the energy needed for each unit of goods, which are important constants in the function. t_{2Ci}, t_{2Mi}, are trip time of car trip and mass transit trip. The trip time is introduced into the function to consider the influence of traffic congestions on energy consumption.

$$E_i = e_1 x_{1i}^* + e_2 t_{2Ci}\left(x_{2Ci}^*, x_{2Mi}^*\right) x_{2Ci}{}^* + e_3 t_{2Mi}\left(x_{2Ci}^*, x_{2Mi}^*\right) x_{2Mi}^* \tag{8}$$

2.5. Energy efficiency

Energy efficiency index UE_i is introduced as Eq. (9). E_i is the individual energy consumption. U_i is the maximum utility level, which represents the personal quality of life in zone i. The index describes the utility level per unit energy consumption. Larger the value of this index is, higher the energy efficiency is.

$$UE_i = \frac{u_i}{E_i} \tag{9}$$

3. Results

We chose Nagasaki metropolitan region for our study. The region is located in Kyusyu island in south of Japan. 88 traffic analysis zones are included in Nagasaki metropolitan region, consisting of three cities (Nagasaki, Isahara, Omura) and four towns. Total of 446,007 of population is distributed over land of 241.20 km^2. The population density is 1,100/km^2.

3.1. Energy consumption

By applying the model, individual energy consumption in Nagasaki is estimated. Table 1 lists the detailed results of energy consumption in 1998.

Table 1 Estimated energy consumption

	1998
Total energy consumption (MJ/person. day)	117.6
Energy consumption for non- mobility goods (MJ/ person. day)	87.1(73.79%)
Energy consumption for car trips (MJ/ person. day)	28.4(24.11%)
Energy consumption for mass transit trips (MJ/ person. day)	2.4 (2.1%)

Note: the number in () indicates the energy share

117.6 MJ of energy is needed for a resident per day in Nagasaki. Consumption of non-mobility goods constitutes more than 73% of total energy consumption, indicated by the value of 87.1 MJ per person each day. Energy use for car trips reaches 28.4 MJ, which is 24.11% of the total energy consumption. There is limited percentage of energy for public transport trips. Averaged 2.4 MJ of energy is used for public transport trips each person per day. The energy share of public transport trips is 2.1%.

3.2. Energy efficiency

According to the energy estimation results and utility level, the energy efficiency in each zone of Nagasaki is shown in Fig. 1. Energy efficiency in zones in the urban central area is higher than those in suburban area. The value of energy efficiency index in the zones along main public transport line is higher than theses in the rest of areas (Fig. 2). Moreover, zones with higher population density are found with higher energy efficiency.

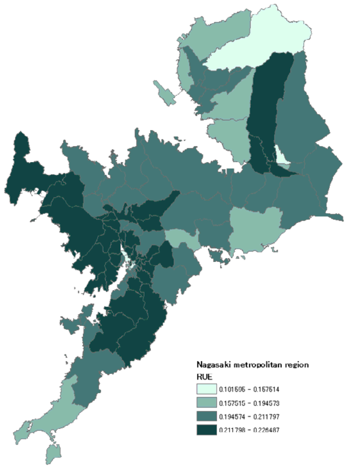

Fig. 1. Energy efficiency of zones

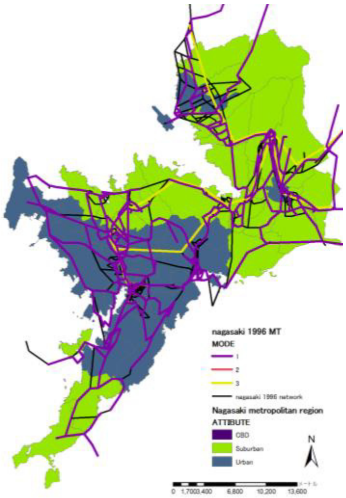

Fig. 2. Network and urban structure of Nagasaki

4. Discussion and Conclusion

This study investigated the relationship between energy consumption and quality of life through an index called energy efficiency. The index describes the utility level per unit of energy consumption. Higher index value means relative high quality of life per energy consumption unit, which indicates more energy saving. By representing the quality of life by utility, a quantitative approach is also put forward to simulate consumption behaviors of residents and estimate energy consumption.

The simulation results indicate three major findings. Firstly, energy consumption is closely related to quality of life. Higher utility level suggests more energy consumption. Second, energy for non-mobility goods and car trips constitute the biggest share of total energy consumption. It suggests energy consumption could be reduced by changing the consumption behaviors, such as substituting car trips by public transit trips. Last but not the least; high energy efficiency could be achieved by compact urban structure and high public transport accessibility. The findings of this study could not only give suggestions for urban planners in Nagasaki, but also expand the field of analysis tool of policy making for governments aiming for low carbon city.

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Biography

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