Research Institute for Environmental Economics and Management

Discussion Paper Series No.2102

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June 2021

WASEDA

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Abstract

Many studies have empirically examined to what extent energy efficiency improvement causes rebound effects for various products. Energy efficiency improvement potentially induces behavioral changes resulting in a rebound effect. However, a limited number of studies have addressed what kind of behavioral changes the energy efficiency improvement of appliances can cause. For example, the energy

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efficiency improvement of air conditioners can induce a change in the room temperature setting. This paper examines whether the energy efficiency improvement of air conditioners impedes energy-saving behaviors. Specifically, using a Japanese household survey, we examined the energy-saving behaviors related to air conditioner usage: 1) setting the room temperature at 28℃ or higher in summer, 2) reducing unnecessary power consumption and 3) cleaning the filters. We found that energy efficiency improvements reduce the probability of the behavior of setting air conditioner temperatures at 28℃ or more by approximately 25–45% during summer, while they have no impacts on the reduction of unnecessary air conditioner usage or filter cleaning. This finding implies that energy efficiency improvements may counteract the energy-saving behaviors of the temperature setting, resulting in a rebound effect. Thus, we clarified a mechanism of the rebound effect in the case of air conditioners.

JEL Code; Q41, Q48 and Q55

Key Words: Energy Saving Behavior, Rebound Effects, Energy Air Conditioner

1. Introduction

Household energy consumption depends partly on the energy efficiency of products (e.g., home appliances and vehicles), as well as the number of products owned. To reduce greenhouse gas emissions from the residential sector, policy makers often introduce measures that promote energy efficiency for products and thereby reduce energy consumption. In the case of Japan, various measures to promote energy efficiency, including energy efficiency standards, information strategies and economic incentives, have been proposed and enacted.[5]

While improved energy efficiency is expected to reduce energy consumption, the reduction also depends on the demand for the energy services provided by products. Energy efficiency improvements reduce energy consumption, thus reducing the unit cost of energy service. This cost reduction provides incentives for individuals to demand more energy services than they did before the energy efficiency improvement. This additional increment in energy services demand offsets the impact of improved energy efficiency on reducing energy consumption (Greening et al., 2000, Sorrell et al., 2009, Gillingham et al. 2016).

This phenomenon, currently known as the rebound effect, was first introduced by William Stanly Jevons in 1865 (Sorrell 2009). Subsequently, following Khazzoom (1980),

[5] The effectiveness of those measures is discussed in Gillingham and Palmer (2014).

the rebound effect has been examined in several studies regarding various energy products and services. For example, Hauseman (1979) examined the rebound effect for air conditioners and estimated the short-term effect (4 %) and long-term effect (26.5 %). Haas and Biermayr (2000) found a 20–30 % rebound effect for space heating. Davis (2008) reported a 5.6 % rebound effect for the washing machine. Furthermore, Matsumoto and Iwata (2016) analyzed hybrid vehicles' driving distance and demonstrated a 23 % rebound effect in the long term. Based on these numerous empirical analyses, researchers and policy-makers have recently recognized the importance of taking into consideration the rebound effect when assessing the outcomes of policies for improving energy efficiency (Gillingham et al. 2016, Vivanco et al. 2016).

Previous studies have not fully examined, however, the mechanisms leading from energy efficiency improvements to incremental demand increases in energy service. In particular, it is not clear which behavioral changes from energy efficiency improvement increase energy demand. Consider, for example, a case where households purchased energy-efficient air conditioners to replace less efficient units. Here, we assume that the electricity consumption of the air conditioner is determined by two operation factors: the hours of air conditioner use (e.g., the operating time per day) and the temperature setting. As shown in Figure 1, the rebound effect for improving energy efficiency emerges from

1) an increase in the operating time and 2) a change in the set room temperature (e.g., lowering the set temperature from 28℃ to 25℃ in summer).

Previous empirical studies have not examined these two behaviors, particularly with regard to air conditioners. Hauseman (1979) measured the rebound effect with electricity bills. Other studies, such as Hass and Biermayr (2000) and Mizobuchi and Takeuchi (2019), used electricity consumption (kWh) to measure the rebound effect. Thus, although these studies showed the existence of the rebound effect, they failed to identify the individual behavioral changes that result in increasing energy consumption.

However, there are some studies that have tried to identify the behavioral mechanism leading from energy efficiency improvements to incremental demand increases in energy service. For instance, Sum (2018) developed a theoretical model and estimated the impact of energy efficiency level on the frequency of using the air conditioner. Although Sum (2018) showed that higher energy efficiency leaded to higher frequency of using air conditioners, it is not clear which behavioral changes from energy efficiency improvement increase energy demand.

This paper explores how energy efficiency improvements of air conditioners affect behaviors related to energy savings. We collect data from a 2010 household-level survey conducted in Japan. From May 2009 to March 2011, the Japanese government implemented a rebate program to encourage the replacement of three varieties of old appliances, namely, air conditioners, refrigerators, and TVs, with more energy-efficient models (Morita, 2015; Morita and Arimura, 2015). Thus, the survey data contain information regarding whether households applied for the program, the extent to which they adopted energy-saving behaviors, and their energy use and social attributes. The behaviors considered in the study are as follows: 1) setting the room temperature at 28℃ or more in summer, 2) switching off unused electrical appliances and 3) clearing the filters. These behaviors are suggested by the Japanese Ministry of the Environment as effective strategies to lower the energy consumption of an air conditioner. We employ a discrete choice model to estimate the effect of energy efficiency improvements on product users' engagement in the three behaviors.

Our estimates show that energy efficiency improvements reduce the probability of the behavior of setting air conditioner temperatures at 28℃ or more by approximately 25–45% during summer. It is also found that energy efficiency improvements do not affect the behaviors of reducing unnecessary power consumption or cleaning filters. In addition, we calculated the direct rebound effect of how much energy consumption increases through behavioral change, by using the estimation results. The calculation result showed that the size of the direct rebound effect through behavioral change was 5.9%-10.6%.

These finding imply that energy efficiency improvements may counteract energy-saving behaviors, resulting in the rebound effect.

The remainder of this paper is structured as follows. Section 2 provides an overview of Japan's energy efficiency policies for household appliances. Section 3 describes the survey data and the estimation model. We then present our estimation results in Section 4. The paper concludes in Section 5, where we discuss policy implications based on the findings as well as the limitations of this study.

2. Energy efficiency policies in Japan

In Japan, various measures have been established to promote energy efficiency. The Japanese government implemented a rebate program, the so-called eco-point program, from May 15, 2009, to March 31, 2011. This program aims to reduce the residential sector's energy consumption and CO_2 emissions by improving the energy efficiency of electrical appliances[6].

The electrical appliances eligible for the points were limited to air conditioners,

[6] This program was meant to promote global warming countermeasures and stimulate the economy after the great recession since 2007 (Ministry of the Environment, Economy, Trade and Industry, Internal Affairs and Communications, 2011).

refrigerators and terrestrial digital broadcasting-compatible TVs and, furthermore, were limited to the appliances with a unified energy-saving label[7] of four or five stars. In the eco-point program, individuals who purchased or replaced energy-efficient appliances could earn eco-points from the government that were exchangeable to gift coupons, pre-paid cards or other products and services. The program also awarded extra recycle points to those who replaced and recycled their products, depending on how much they recycled[8].

Eco-points were issued to 44.81 million applications in total, valuing 639.5 billion yen or 8.11 billion dollars[9] (Ministry of the Environment, Economy, Trade and Industry, Internal Affairs and Communications 2012). On an average, the subsidies were approximately 12,000 yen or 150 dollars per household[10]. Of all points, 72.1% were issued for the purchase of televisions, 16.3% were air conditioners and 11.6% were refrigerators. A total of 66.2% of the points issued (29.67 million applications) were recycle points, meaning that more than half of the purchases during the implementation were made to replace the appliances currently in use with more energy-efficient products.

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[7] This labelling system is composed of four criteria: multi-stage rating system, energy-saving standard achievement rate, energy consumption efficiency based on the Annual Performance Factor index, and expected annual electricity bill. See Morita (2016) for more details on the labelling system.

[8] However, the programme underwent several changes during the campaign period. For example, after November 30, 2010, the number of points issued to buyers was reduced by 50%. After December 31, 2010, points were awarded only for the purchase of products with a unified energy savings label of five stars (i.e., the most energy efficient products), and recycle points were no longer awarded.

[9] One eco-point is counted as one yen. The average annual exchange rate in 2012 (US$1=78.82 yen) is used for the conversion.

[10] The number of households in Japan in 2011 was 57.78 million according to the data of the Residential Basic Register by the Japanese Ministry of Internal Affairs and Communications.

How did the eco-point program impact the energy consumption of home appliances? The products eligible under the program included those with extremely high energy efficiency. The Japanese government established a measure in 1999 setting the energy efficiency standards of various energy-consuming devices. According to the Ministry for Economy, Trade and Industry and the Agency for Natural Resources and Energy (2010), the energy efficiency for air conditioners rose to 67.8% for fiscal year 2004 (compared with fiscal year 1997). As of fiscal year 2010, the energy efficiency of the over-4 kW and under-4 kW classes had improved by 15.6% (compared with fiscal year 2006) and 16.3% (compared with fiscal year 2005), respectively. Air conditioners' energy efficiency improved by 55.2% in fiscal year 2004 (compared with fiscal year 1998) and 43.0% in 2010 (compared with fiscal year 2005). As of fiscal year 2003, CRT TVs had improved by 25.7% (compared with fiscal year 1997), and as of fiscal year 2012, LCD and plasma TV models had improved by 60.6% (compared with fiscal year 2008).

From the above discussion, we can conclude that the eco-point program significantly contributed to the spread of energy-efficient products. However, the energy service demands of devices affect the actual energy consumption. Energy service demand is governed by people's behaviors and decisions as they use appliances. Therefore, price declines in energy services from the program may have reduced the probability of people engaging in energy-saving behaviors as they use the product, which is referred to as the rebound effect.

3. Data and estimation model

3.1 Data

We conducted a household survey in Soka City[11], a suburb of Tokyo, to investigate the relationships between energy efficiency improvement and energy-saving behaviors. The survey was conducted in January and February 2010. At the time, the population of the city was approximately 240,000, with a population density of 8,900/km². This indicates a small population. However, the population density is much higher than Japan's average, which is approximately 300/km².

Our survey methodology was as follows. First, we obtained 1,200 households randomly extracted from a dataset of all households in Soka City[12]. Surveyors visited each selected household and distributed the questionnaire directly to one person per household. The surveyor explained to the respondents that a 500-yen bookstore gift card would be given to them after they answered the questionnaire. Later, the surveyor

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[11] Soka City is a municipality in Saitama Prefecture, approximately 25 km from Tokyo.

[12] We employed a two-stage random sampling method for our survey. First, we selected 60 sites at equal distance from the National Census tracts in Soka City. Next, 20 households were randomly selected from residential map at each site. As a result, the total number of households for our survey was 1,200 (= 60 sits × 20 households per sites).

revisited the household to collect the questionnaire. A total of 714 responses were obtained, with a response rate of 59.5%. However, the sample size of the empirical analysis was only 501 households after incomplete responses were excluded from the dataset.

This analysis focuses on energy-saving behaviors related to air conditioners, as shown in Table 1. These behaviors were recommended by the Japanese Ministry of the Environment and the Energy Conservation Center Japan. We focused on air conditioners because they account for a large part of a household's overall energy consumption.

Engagement in energy-saving behaviors is determined based on the following questions in the questionnaires: "Do you set the air conditioner temperature at 28℃ (or higher)?", "Do you turn off the device when unnecessary?", and "Do you clean the filter once or twice a month?" We asked one representative adult within their family to answer our survey throughout. Furthermore, they were asked to answer the extent to which they were engaged in each behavior with the assumption of a representative air conditioner when they owned multiple air conditioners. In addition, they were asked to answer these questions by choosing "regularly," "sometimes," or "not at all." Table 1 summarizes the engagement pattern for each energy-saving behavior. For the actual analysis, we converted the response to each question to a binary choice value (1 for "regularly" and 0 for “sometimes” and “not at all”).

We asked the respondents whether they had bought an air conditioner using the appliance eco-point program described in Section 2. Their responses are set as the variable *Eco-point program*, which represents energy efficiency improvement. Households who responded “yes” to the question are assumed to be using an air conditioner with better energy efficiency than the unit it replaced. The survey shows that approximately 6% of the respondent households had used the appliance eco-point program in January and February 2010 to buy an air conditioner with higher energy efficiency.

However, the *Eco-point program* variable may suffer from an endogeneity problem. People concerned about energy consumption and the environment are likely to engage in energy-saving behaviors in their daily lives. Such people may have also replaced their old air conditioners with more efficient ones using the appliance eco-point program. People’s degree of concern about energy and the environment is not a variable that we can observe. However, the estimation model representing the relationship between engagement in energy-saving behaviors and energy efficiency improvement includes people’s degree of concern about energy and the environment in the error term. Therefore, the error term and the *Eco-point program* variable may positively correlate. As a result, a positive bias exists in the coefficient of the energy efficiency variable in the model explained in Section 3.2, resulting in erroneous estimates.

Therefore, we used the responses to another question, “Did you move at any time on or after January 1, 2008?” The responses to this question were used as an instrumental variable, *Move*, to check the endogeneity problem. We expected a positive correlation between *Move* and *Eco-point program* variables. The reason is that when a household moves, it often buys new appliances. Moreover, the *Move* variable is expected to be uncorrelated to the error term in the model estimating the relationship between engaging in energy-saving behaviors and improving energy efficiency. In Table 2, we see that 5% of the survey respondents had moved on or after January 1, 2008.

Table 2 also summarizes the social population statistics used as a control variable in the model described in Section 3.2 and descriptive statistics of the variables for household characteristics. These variables include age, gender (1 for male respondents), educational level (1 for college graduates and higher), marital status (1 for married with dependents), household size, number of air conditioners owned, and the difference between the temperature at which the respondent feels comfortable and 28℃. Annual household income was also included as an important control variable. For the analysis, we assigned values of 1, 2, 3, and 4 for annual income of under 3 million yen, 3–5 million yen, 5–10 million yen, and 10 million yen or more, respectively. With regard to residence, we assigned a dummy variable a value of 1 if the respondent owned the residence and recorded its square footage and age.

Finally, we considered how representative the sample from our survey was compared with Soka City in terms of the demographic characteristics. According to the 2010 National Census, the average age of people in Soka City was 42.65, and the population with ages ranging from 19 to 84 was 194,684. Figure 2 shows the distribution of population by age group for the respondents and Soka City, respectively. We found that there were fewer responses from the 20-39 and 80-84 age groups in our sample than in Soka City. Especially, we found that there were fewer responses from the 20-34 age group. In contrast, our survey received more responses from the 40-79 age group. This suggests that the average age of our sample was older than that of Soka City. Therefore, we tested for the independence of these two age-group distributions. In the result, the observed differences were not significant ($p = 0.242$: chi 2 test) .

We found a few differences between our sample and Soka City. First, there was a difference in the marriage status between our sample and Soka City. In our sample, 88.4% of the respondents had married with dependents. In Soka City, however, the people who had married with dependents were 61.4%. This difference can be attributed to the fact that more than half of the respondents in our survey were between the ages of 40 and 64, and there were few responses from the younger age groups. Secondly, there was also a difference in the home ownership between our sample and Soka City. In our sample, 87.4% of the respondents had owned the residence. In Soka City, on the other hand, the percentage of those who owned the residence was 59.1%.

3.2 Estimation model

In this study, we estimate the relationship between engagement in energy-saving behaviors and energy efficiency improvement using the following discrete choice model:

$$Pr(ES_{ij} = 1) = Pr(\alpha_0 + \boldsymbol{\beta}_0\mathbf{X}_i + \gamma EE_i + \varepsilon_i > 0) \quad (1)$$

where ES_{ij} is a dummy variable with a value of 1 when individual *i* answered "regularly" to the question about energy-saving behaviors and 0 otherwise. EE_{ij}, a dummy variable representing energy efficiency improvement, takes the value 1 when individual *i* used the appliance eco-point program to buy a more efficient replacement and 0 otherwise. This variable is the *Eco-point program* described in Section 3.1. $\mathbf{X}_i$ is a vector of control variables, the set of variables used to express the societal and population statistics and household characteristics introduced in Section 3.1. Finally, ε_i is the error term. The error term is assumed to be normally distributed, and we employ a probit model for the estimation.

However, as mentioned in Section 3.1, the potential positive correlation between EE_i and ε_i in Eq. (1) is expected to give rise to a bias in the value of unknown parameter γ. As a test for endogeneity, we followed Tresa et al. (2008) and performed a two-stage residual inclusion (2SRI) estimation. In the first stage, we estimated the following model with endogenous variable EE_i as a dependent variable using a probit regression:

$$Pr(EE_i = 1) = Pr(\alpha_1 + \boldsymbol{\beta}_1\mathbf{X}_i + \delta Move_i + \mu_i > 0) \quad (2)$$

The explanatory variables in Eq. (2) are the control variables also used in Eq. (1), as well as the $Move_i$ variable. This dummy variable takes the value 1 if the individual moved on or after January 1, 2008, and 0 otherwise. This instrumental variable is described in Section 3.1.

In the second stage, we estimate Eq. (3). We include the residuals $\hat{\mu}_i$ predicted by estimating Eq. (2) and endogenous variable EE_i as explanatory variables.

$$Pr(ES_{ij} = 1) = Pr(\alpha_0 + \boldsymbol{\beta}_0\mathbf{X}_i + \gamma_1 EE_i + \gamma_2\hat{\mu}_i + \varepsilon_i > 0) \quad (3)$$

Based on Eq. (3), we can conclude that an endogeneity problem does not exist when the coefficient γ_2 of the error term's predicted value $\hat{\mu}_i$ from Eq. (2) (the first stage) is not significant. Thus, 2SRI has the advantage of being able to discuss Eq. (3) using the same logic as the endogeneity test described by Hausman (1978) (Wooldridge, 2010).

4. Results

4.1 All households

Table 3 shows the estimation results. Columns (1), (3), and (5) of Table 3 summarize the results of Eq. (1). Column (1) shows that the coefficient of the *Eco-point program* variable is significantly negative. In other words, households that bought high-efficiency air conditioners using the appliance eco-point program were unlikely to set air conditioners' temperature as an energy-saving behavior. In contrast, columns (3) and (5) show that energy efficiency improvement variables are not significant. More than half of the respondents answered that they "regularly" turn off the air conditioner when it is not necessary (see Table 1). Therefore, this behavior may be already habitual among all the respondents. This results in the development of an insignificant relationship between the behavior and the Eco-point program. However, the number of respondents who are engaged in the “clean filter” behavior is the lowest; it generally takes more time and effort to clean the filter of air conditioners than the other two behaviors. Alternatively, many people may not know that a clean filter leads to energy-saving. Consequently, it may be presumed that an improvement in the energy efficiency of an air conditioner does not affect the respondents’ decision on whether the filter should cleaned or not.

However, as mentioned in Section 3.2, the *Eco-point program* variable may have an endogeneity problem. Thus, we test for endogeneity using 2SRI. The results for each behavior are shown in columns (2), (4), and (6) of Table 3. First, the results in Eq. (2) show that the *Move* variables are significant. Next, in Eq. (3), the residual values calculated by Eq. (2) are not significant. These finding indicate that no endogeneity problem exists in the variable for energy efficiency improvement. Thus, we adopt the results of Eq. (1) in Table 3 and estimate the average marginal effects in Section 4.3..

Table 3 shows the Eq. (1) estimates for the remaining explanatory variables. Column (1) shows the results on the temperature setting. The results indicate that married households tend to engage in energy-saving behavior related to setting the room temperature. In contrast, households with a large number of family members or with large houses (in square footage) are less likely to set the room temperature in an environmentally friendly manner. We also find that the difference between the temperature perceived as comfortable and 28°C influences the temperature setting. That is, individuals who prefer lower temperatures are less likely to select an environmentally friendly temperature setting.

Column (3) illustrates the results for turning off the air conditioner when it is unnecessary. It shows that individuals with a higher education background and younger individuals are more likely to turn off the air conditioner when it is unnecessary. It was also revealed that those who own a detached house are more likely to engage in the same behaviors.

Finally, column (5) shows the results for filter cleaning and shows that many variables had no significant effects on the behavior of keeping filters clean. However, residence age had a significantly negative impact. In addition, households with annual income in excess of 10 million yen are less likely to clean filters than those with an annual income of 3–5 million yen (baseline).

4.2. Households using one air conditioner

In the analysis above, we implicitly assumed that individuals who used the eco-point program replaced their old air conditioner with a new energy efficient one. However, this may not be the case if individuals engaged in the eco-point program purchased an additional air conditioner. To overcome this problem, we estimate the econometric model by restring our sample to households with a single air conditioner.

Table 4 summarizes the estimation results of a probit model (Eq. (1)) and a 2SRI (Eq. (2) and (3)) after restricting the sample size to households with one air conditioner. The reduced set had 120 observations. In columns (2), (4) and (6), although, the results in Eq. (2) show that the Move variables are significant, the residual values in Eq. (3) are not significant. This finding demonstrates that the energy efficiency improvement variable presents no endogeneity in these estimates, either. Thus, we employ the results of Eq. (1) in Table 4 and estimate the average marginal effects in Section 4.3..

Table 4 illustrates the relationship between energy efficiency improvement and energy-saving behaviors shown in columns (1), (3), and (5). We confirmed that the coefficient of the eco-point program is significant and negative for the energy-saving behavior of setting the room temperature. In contrast, we did not find a statistically significant relationship between the eco-point program and the two other environmental behaviors.

4.3. Impact on energy-saving behaviors and rebound effect

This section discusses the average marginal effect of energy efficiency improvements on the rate of engagement in energy-efficient temperature setting. Here, we employ the results of the probit model (Eq. (1)) in Section 4.1 and 4.2.. Table 5 summarizes the average marginal effect for each variable for energy-saving behavior when setting the thermostat.

Column (1) shows the estimates of the average marginal effects of each variable when the sample size is not constrained. The results showed that individuals who bought more efficient air conditioners engaged in energy-saving behaviors approximately 25% less than those who did not. Column (2) gives the estimates when the sample size is restricted to individuals with only one air conditioner. The results showed that individuals who replaced their old air conditioners with a new energy efficient one are approximately 45% less likely to engage in energy-saving behavior than other individuals.

Finally, we calculated the average direct rebound effect for air conditioners by using our estimates and introducing the following additional assumptions. According to Haas and Biermays (2000), the direct rebound effect is defined by the following equation:

$$\text{Rebound effect}(\%) = \frac{\text{Additional energy uses}}{\text{Expected annual reduction in energy consumptions}} \times 100$$

$$= \frac{\big(\text{Calculated savings}(\text{kWh}) - \text{Actual savings}(\text{kWh})\big)}{\text{Calculated savings}(\text{kWh})} \times 100 \tag{4}$$

where the values of the calculated savings and actual savings are a reduction in the electricity consumption produced by replacing the air conditioner and depending on their specifications.

However, the specifications (except for the cooling capacity) of the air conditioners used in each household were not included in the questionnaires of our survey. Therefore, we made certain relevant assumptions and calculated the direct rebound effects. First, the Japan Refrigeration and Air Conditioning Industry Association (JRAIA)[13] calculated the amount of electricity consumption per year for each air conditioner made in 2000 and 2010 within the 2.8 kW class of cooling capacity. JRAIA calculated that an air conditioner

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[13] Details could be found on this site (https://seihinjyoho.go.jp/catalog/) [only in Japanese; accessed on Feb, 1, 2021].

made in 2000 consumed 1017 kWh (average value per year), while that manufactured in 2010 consumed 872 kWh (average value per year). Using these results, we observe that a reduction of 145 kWh is observed in the electricity consumption (average value per year). Second, the Energy Conservation Center Japan (ECCJ)[14] calculated the annual electricity consumption when the temperature setting of air conditioners is raised from 27℃ to 28℃ in summer. As a result of our calculation based on ECCJ's information, the energy-saving effect was 34.0Wh/h for a cooling capacity of 2.8 kW. Assuming that the air conditioner was used for 9 hours per day for 112 days, the annual reduction in electricity consumption per year was calculated to be 34.27 kWh.

Our estimates showed that the individuals who bought or replaced more efficient air conditioners engaged in energy-saving behaviors, which were approximately 25%-45% less than those who did not. From the result of these estimations, the additional energy used in Eq. (4) were calculated as 8.57kWh-15.42kWh. Furthermore, the magnitude of the direct rebound effects was 5.9%-10.6%.

5. Conclusion

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[14] Details could be found on this site (https://www.eccj.or.jp/dict/index.html) [only in Japanese; accessed on Feb, 1, 2021].

This paper focuses on an aspect of the rebound effect that has not been considered in prior research. We estimate this effect, namely, energy-saving behaviors, and examine the impact of energy efficiency improvements of air conditioners on such behaviors. It is found that the energy efficiency improvements could have a negative impact on energy-saving behaviors, i.e., by leading individuals to set the air conditioner at a lower temperature.

This paper examines a mechanism of the rebound effect that has not been considered in prior research. We estimate the impact of purchasing energy-efficient air conditioners on energy-saving behaviors using a data set of 501 households from a 2010 survey. We employ a probit model to examine the relationship between energy efficiency improvements and energy-saving behaviors. The results show that the people who bought a more efficient air conditioner were less likely than the people who did not replace their air conditioners to engage in the behavior of setting the temperature to 28℃ or above in summer.

However, this analysis of the whole sample above may fail to distinguish additional purchases from replacement purchases; some households may have purchased additional air conditioners using the eco-point program rather than replacing their old unit with a new one. Therefore, we re-estimate the model by restricting the sample to households with only one air conditioner. This analysis also shows that individuals who bought a more efficient air conditioner tend to engage less in the behavior of setting the temperature to 28℃ or above in summer. Thus, we confirm the robustness of our estimation results.

Based on these estimates, we calculate the average marginal effect of energy efficient air conditioner purchase (replacement by the eco-point program) on engagement in the energy-saving behavior of setting the temperature at 28 degrees or above. The results are summarized as follows. First, households that replaced their air conditioners with a more efficient model are approximately 25% less likely to be engaged in the behavior of setting the temperature to 28℃ or above in summer. Second, in the case of the restricted sample, it is found that households that replaced their old air conditioner with a new energy efficient unit are approximately 44.5% less likely to engage in such behavior. Hence, we conclude that energy efficiency improvements through the purchase of new energy-efficient appliances are likely to counteract engagement in environmentally friendly temperature setting. In addition, we calculated the direct rebound effect of how much energy consumption increases through behavioral change, by using the estimation results. The calculation result showed that the size of the direct rebound effect through behavioral change was 5.9%-10.6%. Thus, we clarified a mechanism of the rebound effect in the case of air conditioners.

However, we note a limitation of our study. We could not analyses changes in the hours of air conditioner usage. Thus, this study does not assess all behaviors related to energy consumption for air conditioners. For future research, we would like to collect data on how long people turn on their air conditioners to assess the extent of the rebound effect in a more accurate manner across all such behaviors.

Japan has achieved major progress in promoting energy efficiency under several programs, such as the eco-point program and energy efficiency standards. The diffusion of energy-efficient appliances will contribute to the reduction of energy consumption and CO_2 emissions. However, our results show that energy efficiency improvements may counteract certain energy-saving behaviors. As noted in Section 2, 66% of those who used the appliance eco-point program made replacement purchases to improve energy efficiency, implying that the program caused a rebound effect to some extent.

One may inquire about the type of supplemental policy that could deal with this type of rebound effect at the behavioral level. It would be effective for policy makers to induce technological innovation that does not encourage users to change their energy-saving behaviors. One possible approach is to promote the introduction of artificial intelligence (AI) rather than individual environmental conservation behaviors. This approach would enable products to adjust their temperature setting automatically. New models of air conditioners with this feature are already being launched in the market. However, they are more expensive than other models. Subsidies for such new appliances that induce no behavioral changes may be effective as extrinsic incentives.

Acknowledgements

We appreciate the financial support from Japan Society of the Promotion of Science. Kakenhi Grant number 15H03352, 18H03433 and 19K20510. Minoru Morita is financially supported from Research Encouragement Grant by Takasaki City University of Economics. We are thankful for the helpful comments from Kenich Mizoguchi and participants at 20th Annual Conference of Society for Environmental Economics and Policy Studies in 2015.

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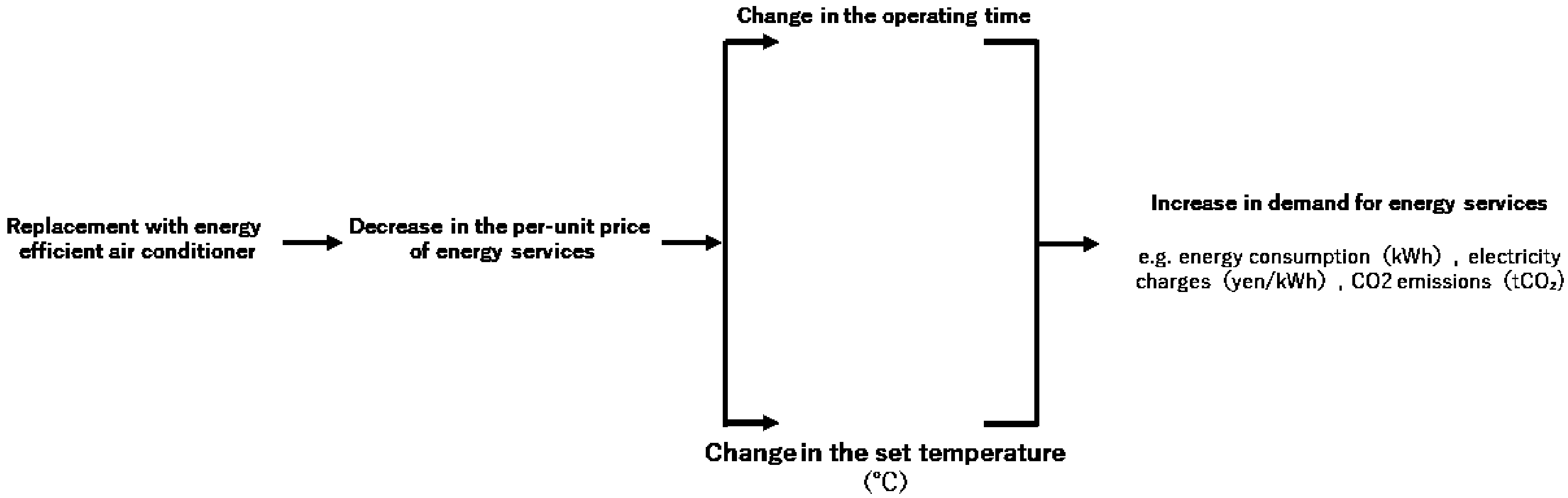
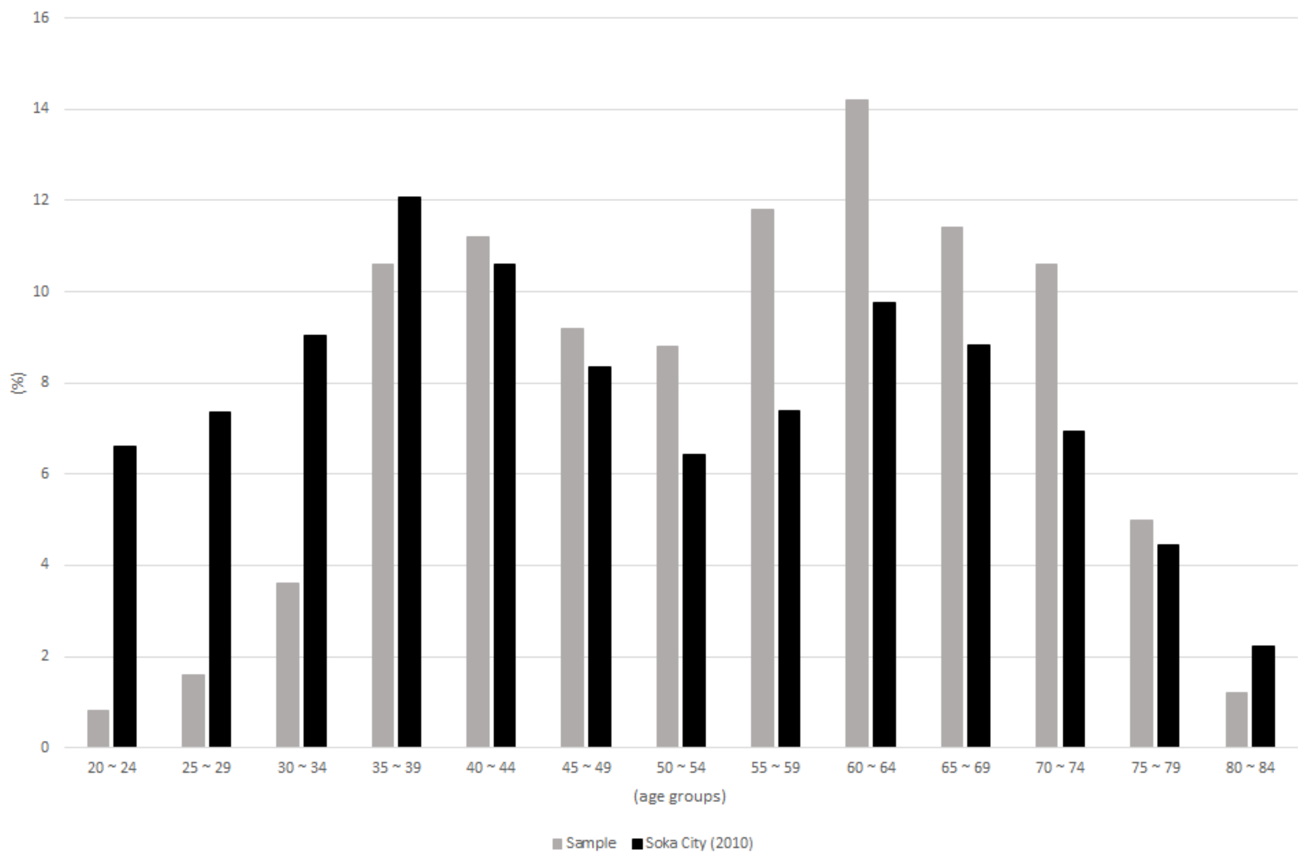


Fig 1. The rebound effect for air conditioners



Note1: Sample size of our survey was 500 (Excluding one sample that answered 19 years old.)

Note2: The population of Soka City between the age of 20 and 84 was 192,199.

Fig.2: The age structure of population

Table 1. Percentage Engaging in Energy-Saving Behaviors

Equipment	Energy-saving action	regularly	sometimes (%)	not at all
Air conditioner	Set to 28 degrees in summer	37.1	57.5	5.4
	Turn off when unnecessary	52.9	41.9	5.2
	Clean filters	29.1	55.9	15.0

Note: The number of observations is 501.

Table 2. Descriptive Statistics

Variable	Mean	Std. Dev.	Min	Max
Income (scale variable)				
less than 3 million yen	0.19	0.40	0	1
3 million to 5 million yen	0.30	0.46	0	1
5 million to 10 million yen	0.40	0.49	0	1
more than 10 million yen	0.11	0.31	0	1
Age	54.82	13.77	19	84
Male	0.32	0.47	0	1
Education (Bachelor's degree or higher)	0.23	0.42	0	1
Married	0.88	0.32	0	1
Number of family members	3.36	1.35	1	7
Own house	0.87	0.33	0	1
House size (number of rooms)	4.88	1.48	1	10
House age	19.23	11.47	0	50
Number of air conditioners	2.34	1.02	1	4
28°C − Comfortable temperature in summer	2.13	1.96	-2	10
Eco-point program	0.06	0.24	0	1
Move	0.05	0.22	0	1

Note: The number of observations is 501.

Table 3. Estimation results

	Set to 28 degrees in summer				Turn off when unnecessary				Clean filers			
	(1)		(2)		(3)		(4)		(5)		(6)	
	Probit model (1)		2SRI (1)		Probit model (1)		2SRI (1)		Probit model (1)		2SRI (1)	
	Coefficient	z-statistic	Coefficient	z-statistic	Coefficient	z-statistic	Coefficient	z-statistic	Coefficient	z-statistic	Coefficient	z-statistic
Eco-point program	-0.7572	-2.46 **	-0.4761	-0.33	-0.0008	0.00	0.6947	0.46	0.0881	0.37	-0.4093	-0.27
less than 3 million yen	0.0939	0.48	0.0864	0.43	0.1823	1.01	0.1647	0.89	-0.0351	-0.19	-0.0226	-0.12
5 million to 10 million yen	0.1175	0.79	0.1096	0.7	0.0232	0.16	0.0022	0.01	0.1174	0.79	0.1327	0.87
more than 10 million yen	-0.1475	-0.67	-0.1445	-0.66	-0.2715	-1.33	-0.2642	-1.28	-0.5163	-2.08 **	-0.5218	-2.1 **
Age	-0.0095	-1.62	-0.0099	-1.58	-0.0178	-3.14 ***	-0.0189	-3.15 ***	0.0023	0.39	0.0031	0.51
Male	0.1349	0.99	0.1372	1.01	0.0039	0.03	0.0093	0.07	0.0098	0.07	0.0060	0.04
Education (Bachelor's degree or higher)	0.2315	1.57	0.2307	1.57	0.2803	1.95 *	0.2794	1.94 *	-0.1059	-0.69	-0.1059	-0.69
Married	0.4529	2.12 **	0.4291	1.76 *	0.1150	0.57	0.0601	0.26	0.3232	1.44	0.3631	1.43
Number of family members	-0.2094	-3.47 ***	-0.2061	-3.31 ***	-0.1457	-2.71 ***	-0.1389	-2.48 **	-0.0315	-0.54	-0.0366	-0.6
Own house	0.2572	1.17	0.2686	1.16	0.3582	1.69 *	0.3892	1.78 *	0.2679	1.23	0.2461	1.09
House size (number of rooms)	-0.0132	-2.08 **	-0.0129	-1.96 *	-0.0107	-1.77 *	-0.0099	-1.58	0.0095	1.53	0.0089	1.39
House age	-0.0297	-0.57	-0.0297	-0.57	0.0030	0.06	0.0030	0.06	-0.0988	-1.85 *	-0.0987	-1.85 *
Number of air conditioner	-0.0775	-1.29	-0.0772	-1.28	0.0273	0.51	0.0277	0.52	0.0212	0.36	0.0209	0.36
28°C − Comfortable temperature in summer	-0.1681	-4.28 ***	-0.1704	-4.19 ***								
Constant	1.0707	2.57 **	1.0780	2.57 **	1.1728	2.97 ***	1.1812	2.99 ***	-0.8293	-2.13 **	-0.8374	-2.16 **
Residual error			-0.2914	-0.19			-0.7145	-0.47			0.5115	0.34
Move (1st stage)			1.3847	2.09 **			1.3852	2.10 **			1.3852	2.10 **
Log pseudolikelihood	-292.88		-292.86		-329.04		-328.91		-292.80		-292.74	
Wald chi2	59.52		59.57		31.93		32.87		15.26		15.47	
Prob > chi2	0.00		0.00		0.00		0.00		0.29		0.35	
Pseudo R2	0.11		0.11		0.05		0.05		0.03		0.03	
Number of obs	501											

Note: ***, ** and * denote significance at the 1%, 5%, and 10% levels, respectively.

Table 4. Estimation results

	Set to 28 degrees in summer				Turn off when unnecessary				Clean filers			
	(1)		(2)		(3)		(4)		(5)		(6)	
	Probit model (2)		2SRI (2)		Probit model (2)		2SRI (2)		Probit model (2)		2SRI (2)	
	Coefficient	z-statistic	Coefficient	z-statistic	Coefficient	z-statistic	Coefficient	z-statistic	Coefficient	z-statistic	Coefficient	z-statistic
Eco-point program	-1.5532	-2.81 ***	-1.4885	-0.9	-0.5160	-1.11	-2.0801	-1.34	-0.3627	-0.77	-2.4083	-1.3
less than 3 million yen	0.8296	2.05 **	0.8197	1.8 *	0.1381	0.36	0.3704	0.86	-0.1201	-0.33	0.1627	0.39
5 million to 10 million yen	-0.1730	-0.49	-0.1802	-0.46	-0.2044	-0.63	-0.0408	-0.11	-0.2446	-0.75	-0.0218	-0.06
more than 10 million yen	-0.8299	-1.46	-0.8359	-1.43	-0.4243	-0.81	-0.2901	-0.53	-0.7323	-1.08	-0.5377	-0.77
Age	0.0099	0.71	0.0098	0.69	0.0121	1.00	0.0146	1.19	0.0199	1.73	0.0235	1.94 *
Male	0.0659	0.23	0.0636	0.22	0.1127	0.40	0.1815	0.63	0.2400	0.80	0.3300	1.06
Education (Bachelor's degree or higher)	0.1978	0.64	0.1926	0.59	0.1802	0.61	0.2807	0.89	-0.0889	-0.29	0.0362	0.11
Married	0.5912	1.44	0.5853	1.36	-0.0570	-0.15	0.0713	0.18	0.0967	0.25	0.2646	0.67
Number of family members	0.0080	0.05	0.0067	0.05	-0.0640	-0.50	-0.0360	-0.27	0.2841	1.96 *	0.3271	2.13 **
Own house	0.0025	0.01	0.0043	0.01	-0.0129	-0.04	-0.0962	-0.28	0.1763	0.48	0.0811	0.22
House size (number of rooms)	-0.0308	-2.09 **	-0.0307	-2.05 **	-0.0356	-2.47 **	-0.0384	-2.79 ***	-0.0040	-0.30	-0.0060	-0.43
House age	-0.0138	-0.10	-0.0127	-0.09	0.0779	0.73	0.0575	0.54	-0.1344	-1.06	-0.1575	-1.22
28°C – Comfortable temperature in summer	-0.3771	-4.88 ***	-0.3772	-4.88 ***								
Constant	0.0209	0.02	0.0299	0.03	0.0858	0.12	-0.0961	-0.13	-1.8206	-2.45 **	-2.1644	-2.83 ***
Residual error			-0.0792	-0.05			1.7679	1.07			2.3425	1.27
Move (1st stage)			1.3847	2.09 **			1.3852	2.10 **			1.3852	2.10 **
Log pseudolikelihood	-61.51		-61.51		-76.92		-76.24		-70.00		-69.09	
Wald chi2	41.40		42.15		12.13		14.3		10.51		11.34	
Prob > chi2	0.00		0.00		0.44		0.35		0.57		0.58	
Pseudo R2	0.24		0.24		0.08		0.08		0.08		0.09	
Number of obs						120						

Note: ***, ** and * denote significance at the 1%, 5%, and 10% levels, respectively.

Table 5. The average marginal effects of setting the thermostat

	Average Marginal Effects			
	Probit model (1)		Probit model (2)	
Eco-point program	-0.2527	**	-0.4452	***
less than 3 million yen	0.0313		0.2378	**
5 million to 10 million yen	0.0392		-0.0496	
more than 10 million yen	-0.0492		-0.2379	
Age	-0.0032		0.0028	
Male	0.0450		0.0189	
Education (Bachelor's degree or higher)	0.0773		0.0567	
Married	0.1512	**	0.1695	
Number of family members	-0.0699	***	0.0023	
Own house	0.0859		0.0007	
House size (number of rooms)	-0.0044	**	-0.0088	**
House age	-0.0099		-0.0040	
Number of air conditioners	-0.0259			
28°C − Comfortable temperature in summer	-0.0561	***	-0.1081	***

Note: ***, ** and * denote significance at the 1%, 5%, and 10% levels, respectively.