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Efficiency Investment and Curtailment Action

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Abstract

Households' energy-saving activities are often categorized into efficiency investment and curtailment action, which previous studies have analyzed separately, even though households use both activity types simultaneously. In this study, we develop an energy-saving model based on a household production framework to show how these two activities are related. Our household production framework predicts that a household uses energy efficiency investment and curtailment action jointly and not alternatively. Specifically, a household that invests heavily in energy efficiency spends more time on curtailment action . Our empirical analysis uses micro-level data from the Survey on Carbon Dioxide Emissions from Households in Japan to examine the validity of this prediction in a real-world setting. We compare the intensities of curtailment actions by households that keep using old appliances beyond the appropriate replacement period with those by households that use appliances within an appropriate replacement cycle. Our empirical results reveal that the former households, which do not invest in energy efficiency adequately, are less engaged in curtailment actions than the latter households, which invest in energy efficiency adequately. Therefore, the empirical results support the theoretical prediction.

Keywords Curtailment action · Efficiency investment · Household energy saving · Micro-level data

JEL Classification D13 · J22 · Q41

1 Introduction

Governments have introduced various regulatory measures to increase the energy efficiency of energy-consuming products (e.g., Agency of Natural Resources and Energy of

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Japan 2019; European Commission 2019) while simultaneously promoting energy-efficient products to households (e.g., European Union 2020; U.S. Department of Energy 2019). By investing in the energy efficiency of energy-consuming products, households can lower the effective price of the energy service and thus, can reduce energy consumption without lowering the energy service level. However, households need to incur additional expenses to install new energy-efficient products, since the prices of these products are higher than those of conventional products.

Many households have long adopted curtailment actions, such as turning off unused lights and unplugging charging devices. In recent years, power companies have introduced various experimental behavioral programs to change the energy usage habits of households. Some researchers have participated in the program design and have evaluated the effectiveness (Allcott and Mullainathan 2010; Allcott 2011; Tiefenbeck et al. 2013; Frederiks et al. 2015). Although households do not need to spend money when taking such curtailment actions, they are required to spend time on these actions.

Thus, households can adopt two types of energy-saving activities: efficiency investment and curtailment action. While money is a crucial factor in efficiency investment, time is often a crucial factor in curtailment action. Since the relative importance of money and time varies between households (Gronau and Hamermesh 2006, 2008), it is natural to expect that the optimal combination of efficiency investment and curtailment action varies between households. How are the optimal combinations of efficiency investment and curtailment action related? Would households lower curtailment action if the price of energy-efficient products were to decrease? Would households stop practicing energy-saving activities after purchasing new energy-saving products? To answer these questions, this study develops an energy-saving model based on a household production framework.

We assume that a household receives utility from entertainment activity and energy service. Market goods and leisure time are necessary for entertainment activity. We further assume that a household allocates time among market work, leisure, and curtailment action. If household members work longer hours outside the home and spend more time on leisure, they can enjoy more entertainment activity. However, in that case, they need to cut back time spent on curtailment action and pay higher energy bills. Instead of spending time on curtailment action, a household can purchase energy-efficient products. Although the household can lower the effective price of the energy service through investment in energy efficiency, it needs to reduce the amount of market goods purchased. The household's energy-saving activity is characterized by a production function with two inputs: efficiency investment and curtailment action. Using this household production framework, we arrive at the following theoretical findings.

We show that efficiency investment and curtailment action become substitutes if a household's utility is given by a Cobb–Douglas function. By contrast, efficiency investment and curtailment action can become either complements or substitutes if a household's utility is given by a constant elasticity of substitution (CES) function. If the energy-efficient products become expensive, then the household substitutes curtailment action for efficiency investment. This first cross-price effect within energy-saving activity enhances the substitution between the two energy-saving measures. However, the price increase of energy-efficient products makes energy-saving activities more costly and thus, the cost of the energy service rises more than that of entertainment activity. Consequently, the household reduces its energy service consumption and increases its entertainment activity. This second cross-price effect lowers the energy-saving activity and thus, the time spent on curtailment action is reduced. The second cross-price effect becomes the driving force for inducing a complementary relationship between efficiency investment and curtailment action. In this study, we derive the necessary and sufficient condition for making efficiency investment and curtailment action become complements.

It is difficult to accurately measure the financial cost of energy efficiency investment and the time cost of taking curtailment action. In our empirical study, instead of investigating how the price change in energy-efficient products affects energy-saving practice, we directly examine the relationship between efficiency investment and curtailment action. For this purpose, we analyze micro-level data from the Survey on Carbon Dioxide Emission from Households (SCDEH) (Ministry of the Environment of Japan 2014, 2017, 2018). In the SCDEH, households are asked about their energy-saving practices together with the age of their electric appliances. The inclusion of information about both energy-saving practices and the age of electric appliances is the major strength of the SCDEH dataset. Other datasets typically used in appliance usage analyses do not satisfy this condition; for example, the US Residential Energy Consumption Survey (RECS) does not include information about energy-saving practices.

The Japanese government introduced a regulation called the Top Runner Program in 1999. This program requires manufacturers to achieve the energy efficiency of the most efficient appliance selling in the market at the time of the program implementation by the target year. Therefore, the program guarantees that the energy efficiency of appliances will improve over time. Because the Top Runner Program's standards being reviewed approximately every 5 years, the energy efficiency of air conditioners (ACs) increased by 78.85% from 1997 to 2010, that of refrigerators (REFs) increased by 78.94% from 1998 to 2010, and that of LCD TVs increased by 47.54% from 2014 to 2012. From 2010 to 2020, the energy efficiency of ACs and REFs improved by 12% and 37–43%, respectively (Agency of Natural Resources and Energy 2015, 2022).

Although the replacement of old appliances yields a clear energy conservation effect, many households continue to use old appliances beyond the appropriate replacement period. The Japanese government has strongly encouraged households to replace appliances that have passed the appropriate replacement period, which is about 10 years (Ministry of the Environment of Japan 2022).

In the empirical section, we examine whether there is a difference in the intensity of curtailment actions between households that keep using old appliances beyond the appropriate replacement period and remaining households. Although the age of an appliance is not perfectly correlated with its energy efficiency,[1] we consider the age to be a good proxy variable of product energy efficiency, given the requirements of the Top Runner Program and the drastic energy efficiency improvements over the last 30 years. In addition, most households have limited ability to understand the technical aspects of the energy efficiency of home appliances. For this reason, Energy Star labels are used in many countries. Since it is not realistic to ask households to check the energy efficiencies of their appliances, the government recommends that households gauge the energy efficiency of appliances based on their age. Therefore, an age-related analysis of appliances is consistent with real policies.

Our empirical results reveal that households that keep using old appliances are less engaged in curtailment actions than remaining households. This result indicates that households jointly use efficiency investment and curtailment action. We believe that our empirical findings have important implications for energy policy. If households weaken

[1] The age of appliances has been used as a proxy for energy efficiency in previous studies (Rapson 2014; Tsvetanov and Segerson 2014).

curtailment actions after purchasing energy-efficient products, then the promotion policies for energy-efficient products by many governments would crowd out voluntary energy-saving behavior by households. By contrast, the complementary relationship found in this study suggests that governments can promote energy-efficient products without being concerned about crowding-out problems arising.

The rest of this paper is organized as follows. In the next section, we review the literature on households' energy-saving behavior. In Sect. 3, we develop an energy-saving model based on a household production framework to show the relationship between efficiency investment and curtailment action. For the empirical analysis, we use data from the SCDEH. In Sect. 4, we provide information about the SCDEH and summarize the socioeconomic characteristics of households that participated in the survey. We also report energy-saving practices of households. We present the estimation model and report the empirical findings in Sect. 5. We conclude with the policy implications of our findings in Sect. 6.

2 Literature Review

Researchers have classified energy-saving measures from various viewpoints. For example, Boudet et al. (2016) systematically assessed 261 varieties of energy-saving measures according to nine attributes: energy savings, cost, frequency of performance, required skill level, observability, locus of decision, household function, home topography, and appliance topography. Boudet et al. (2016) classified energy-saving measures into four types: family style, call an expert, household management, and weekend project. Although there are many other classifications of energy-saving measures, the most popular is that between energy investment and curtailment action (Karlin et al. 2014). Curtailment action consists of habitual and daily practices that do not require much financial resource. Curtailment action includes energy-saving actions, such as turning off the lights in empty rooms, adjusting the AC temperature appropriately, and avoiding overstuffing the REF. On the other hand, efficiency investment consists of non-routine activities that require financial resources. Energy-saving investments include replacement of home appliances and housing renovation.

Using micro-level data, researchers have analyzed household energy-saving behaviors. Earlier studies have focused on market failures caused by principal–agent problems in both efficiency investments and curtailment actions (Ramos et al. 2016). Brechling and Smith (1994) used micro-data from the 1986 English House Condition Survey and estimated logit models to identify the factors influencing the pattern of possession of three energy efficiency measures: loft insulation, wall insulation, and double glazing. They found that the rates of possession of these three measures in private rented properties were much lower than those in owner-occupied properties. The literature has also estimated reduced-form logit models of the factors influencing the pattern of possession of the three principal energy efficiency measures—loft insulation, wall insulation, and double glazing. Maruejols and Young (2011) analyzed micro-level data from the 2003 Canadian Survey of Household Energy Use and found that renters set room temperature higher in winter if their rent payment includes the energy bill. Hence, the authors confirmed that households do not take energy-saving actions if they do not have to pay energy bill themselves. Maruejols and Young (2011) also found that income has no influence on the setting of room temperature, but affects eco-friendly behavior. Although tenants have little incentive to conserve energy, energy costs are included in the rent of many US apartments. Levinson and Niemann

(2004) used US data from the RECS and the American Housing Survey, to explain this market failure. Although apartment rents that include energy costs are higher than those of comparable metered apartments, the difference in rents is relatively small. Based on this empirical finding, the authors argued that a market failure exists because the lessors value the contracts more than the cost of that extra energy.

In recent years, researchers have analyzed the determinants of both efficiency investments and curtailment actions. Urban and Ščasny (2012) used the data of 9242 households from a survey conducted in 10 OECD countries in 2008, and estimated a structural equation model to examine how socioeconomic characteristics and environmental attitudes of households affect five curtailment actions and five efficiency investments. The authors confirmed that (1) age positively affects both curtailment actions and efficiency investments, and (2) income has a positive impact on efficiency investments but a negative impact on curtailment actions. In addition, they reported that education and gender have no strong impact on both efficiency investments and curtailment actions, and that large households invest in energy efficiency.

Wang et al. (2011) studied the willingness to save energy of 816 households in Beijing. They reported that economic benefits, government policy and advertising, and perceived inconvenience are important determinants of energy-saving behaviors among Chinese households. Meanwhile, they found that environmental knowledge, including climate change, does not affect willingness to save energy. With respect to variables for socioeconomic characteristics, Wang et al. (2011) found that although age enhances willingness to save energy, but other socioeconomic characteristics, such as income and education, have no effect.

Mills and Schleich (2012) investigated the determinants of curtailment actions and efficiency investments of approximately 5000 households from the Residential Monitoring to Decrease Energy Use and Emissions in Europe Project survey conducted in 10 EU countries and Norway. With regard to energy efficiency investments, factor analysis was conducted based on the holding status of energy-efficient products related to REFs, freezers, dishwashers, washing machines, dryers, office equipment, and lighting. For curtailment actions, factor analysis was conducted based on six energy-saving actions: (1) fully loading the washing machine every time; (2) cooking frequently with a pressure cooker; (3) turning off the lights every time a room is vacated; (4) turning off the TV when it is not being watched; (5) setting energy-saving features on the computer monitor; and (6) setting energy-saving features on the computer desktop. Mills and Schleich (2012) reported that households with young children are more likely to invest in energy efficiency and take curtailment actions. Furthermore, they reported that education is positively associated with both efficiency investments and curtailment actions.

Nakamura (2013) surveyed the practice of 45 varieties of energy-saving behaviors in the year after the Tohoku Great Earthquake of about 1000 households living in Kanagawa prefecture, Japan. Although he found that women actively practiced energy-saving behaviors, he did not find an effect of income and age. He further observed social interactions about energy-saving practices and argued that it would be effective to provide information about energy-saving measures to those who actively interact with others outside the home.

Brounen et al. (2013) used the data of 1721 households from the 2011 Dutch National Bank Household Surveys and analyzed both room temperature setting and night temperature control. They found that gender has no impact on either temperature settings or temperature control. However, they found that seniors set the room temperature higher and did not lower the temperature even at night. Although high-income households set the room temperature higher than low-income households, there is no difference in night temperature control between the two.

Hori et al. (2013) used a 2009–2010 energy-saving survey on lighting, TVs, REFs, and ACs in five Asian cities (Dalian, Chongqing, Fukuoka, Bangkok, and Ho Chi Minh), and compared the determinants of energy-saving behaviors across countries. They confirmed that interest in global warming, environmental behavior, and social connections have a strong influence on energy-saving behaviors. They also confirmed that income and age have a weak positive impact on energy-saving behaviors. Although their research has the advantage of providing an international comparison, it lacks preciseness, since the energy-saving behaviors they considered are less specific.

Traynor et al. (2014) used micro-level data of about 6000 households from the 2008–2009 British Household Panel Survey (BHPS), which investigated whether respondents who stated that energy saving is an important global environmental problem adopted energy-saving behaviors at home. The authors studied heating expenses, since it is less likely to be checked by outsiders. They found that (1) high-income households spend more on heating; (2) there is an inverse U-shaped relationship between age and heating expenses; and (3) neither number of children nor employment status affects heating expense. Although general concern about environmental problems has no influence on heating costs, households adopting pro-environmental behaviors in daily life consume less energy. In addition, households whose members consider that they have less time required for pro-environmental behaviors consume less energy.

Lange et al. (2014) also used BHPS data to examine whether environmental behaviors, beliefs, and attitude are associated with space heating energy use. They found that environmental behaviors are negatively correlated with heating expenditures, while environmental attitudes and perceptions are not associated with low heating expenditure. The authors further found that the effect of these attitudes and behaviors is maintained regardless of income level. Given these empirical observations, they rejected the green hypocrisy hypothesis, namely, that people with a strong attitude toward the environment use more energy.

Lillemo (2014) analyzed the data of approximately 900 households from a TNS Gallup web-panel survey conducted in Norway in 2011 and found that people who keep postponing planned tasks or decisions engage in neither curtailment actions nor efficiency investments. In addition, the authors found evidence of the so-called low-cost hypothesis, namely, that people with high environmental awareness engage in low-cost curtailment actions but do not necessarily engage in high-cost energy investments. Lillemo (2014) reported several findings: (1) income has a positive effect on efficiency investments but a negative effect on curtailment actions; (2) education has a positive effect on curtailment actions but no effect on efficiency investments; (3) young people do not take curtailment actions; and (4) women are less active in efficiency investments than men.

Botetzagias et al. (2014) conducted an original survey of 285 Greek households to establish the determinants of seven curtailment actions: (1) last person switches off all the lights when leaving a room; (2) set the washing machine's temperature to 60 °C instead of 90 °C; (3) do not load the washing machine to a completely full level; (4) turn off the main switch of the TV when nobody is watching; (5) switch off the computer when not in use; (6) switch electric devices to stand by when not in use; and (7) put a lid on the pot when boiling food. Botetzagias et al. (2014) confirmed that different types of energy-saving behavior are decided by different factors but confirmed that both psychological and socioeconomic factors are important in any energy-saving action.

Ramos et al. (2016) analyzed the data of 27,000 households from the 2008 survey, 'Encuesta Social: Hogares y Medio Ambiente' (Social Survey, Households, and the Environment). They found that pro-environmental households invest in energy efficiency (purchase of energy-efficient appliances, double-glazed windows, and energy-saving lightbulbs) and take curtailment action (temperature control) more frequently. By contrast, the authors found that households' willingness to pay for environmental protection has no influence on energy-saving behaviors. They further found evidence for the low-cost hypothesis, namely, that pro-environmental households do not invest in energy efficiency when investment costs are high. In addition, Ramos et al. (2016) showed that households with high income and education invest in energy efficiency but do not take curtailment actions. Elderly households neither invest in energy efficiency nor engage in curtailment actions.

Using data of 2356 French households from PHEBUS[2] conducted in 2014, Belaid and Garcia (2016) estimated individuals' "energy-saving ability" from multiple energy-saving practices based on item response theory. Then, they used Lasso to identify the determinants of energy-saving ability. They confirmed that (1) higher energy price promotes energy-saving behavior; (2) people living in less energy-efficient households adopt energy-saving behavior; and (3) there is a U-shaped relationship between age and energy-saving behavior. Meanwhile, the authors found that income and education have no impact on energy saving ability.

Using data from the Survey of Public Attitudes and Behaviours towards the Environment conducted in the UK in 2009, Trotta (2018) investigated the determinants of both curtailment actions and efficiency investments (purchase of energy-efficient appliances and housing renovations). The determinants of these three energy-saving behaviors were estimated by three separate equations. They classified six types of curtailment actions based on principal component analysis. Subsequently, they studied the effect of socioeconomic characteristics, housing characteristics, and environmental attitudes of the subject on three energy-saving behaviors. Trotta (2018) found that (1) environmental attitudes influence both curtailment actions and purchase of energy-efficient appliances, but do not influence housing renovations; and (2) there are very different impacts of income and housing characteristics on curtailment actions versus housing renovation.

This section reviews studies that evaluated energy-saving behaviors (curtailment actions and efficiency investments) based on an analysis of micro-level data. We summarize their findings in Table 1.

1. High income is positively associated with efficiency investments but is often negatively associated with curtailment actions.
2. Age is positively associated with efficiency investments and has an inverse U-shaped relationship with curtailment actions.
3. Some scholars consider that education has a positive impact on efficiency investments.
4. Environmental concern may enhance both curtailment actions and efficiency investments.

Therefore, previous studies have not fully identified the socioeconomic characteristics of people adopting energy-saving behaviors. More importantly, no previous study has considered the simultaneous use of curtailment actions and efficiency investments. Even in works

[2] PHEBUS is a French acronym corresponding to: Housing performances, equipment, needs, and usages of energy.

Table 1 Empirical findings from previous studies

Study	Region	Years	Size	Type of energy saving	
Trotta (2018)	UK	2009	2009	Curtailment	Index
				Efficiency	Energy efficient appliance
					Housing renovation
Belaid and Garcia (2016)	France	2014	About 2350	Curtailment	Energy saving ability
Ramos et al. (2016)	Spain	2008	About 27,000	Curtailment	Room temperature
				Efficiency	Appliance, Light bulb
					Double glazing
Traynor et al. (2014)	UK	2008	5981–6052	Curtailment	heat expenditure
Lillemo (2014)	Norway	2011	966–970	Curtailment	Room temperature, Warm up limited rooms
				Efficiency	Wall insulation, heating equipment
Lange et al. (2014)	UK	2008–2009	6044–6370	Curtailment	Energy usage for space heating
Brounen et al. (2013)	Netherlands	2011	1721	Curtailment	Room temperature
Mills and Schleich (2012)	11 European countries	2007	4915	Curtailment	Index
				Efficiency	Index, Light bulb
Maruejols and Young (2011)	Canada	2003	931	Curtailment	Room temperature
Urban and Ščasny (2012)	10 OECD countries	2008	9242	Curtailment	5 Varieties of activities
				Efficiency	5 Varieties of activities
Brechling and Smith (1994)	UK	1986	5271–6395	Efficiency	Loft install, wall insulation, double glazing

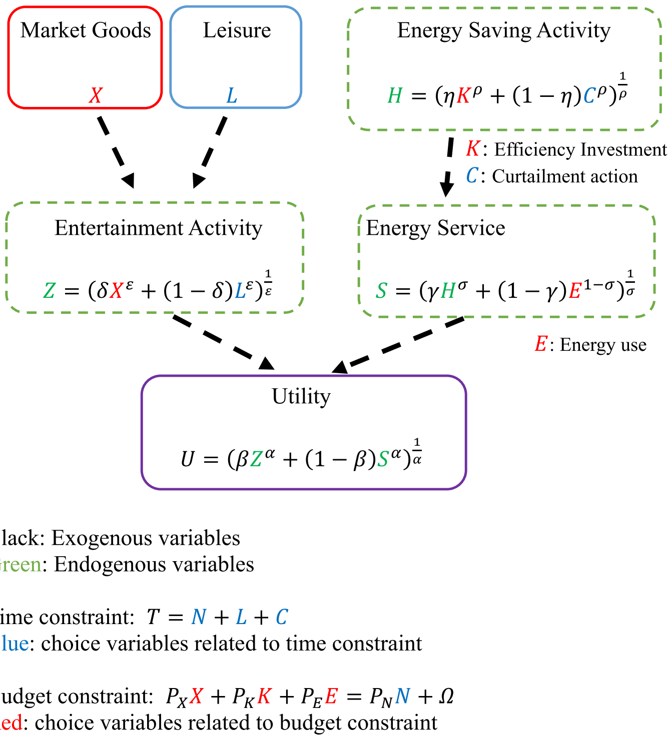

Fig. 1 Structure of household production model

that analyze both curtailment actions and efficiency investments, these two energy-saving behaviors have been analyzed separately.

3 Theoretical Model

3.1 The Structure of Household Production Model

The structure of our household production model is depicted in Fig. 1. A household obtains utility U from entertainment activity Z and energy service S. We assume that the household utility function is given by the CES utility function $U = (\beta Z^{\alpha} + (1-\beta)S^{\alpha})^{\frac{1}{\alpha}}$ where $\alpha \leq 1$ and $0 < \beta < 1$. The household needs market goods X and leisure time L to enjoy the entertainment activity Z. It is assumed that the entertainment activity is characterized by the CES production function $Z = (\delta X^{\varepsilon} + (1-\delta)L^{\varepsilon})^{\frac{1}{\varepsilon}}$ where $\varepsilon \leq 1$ and $0 < \delta < 1$. If the household engages in energy-saving activity H and consumes energy E, then it receives energy service $S = (\gamma H^{\sigma} + (1-\gamma)E^{\sigma})^{\frac{1}{\sigma}}$ where $\sigma \leq 1$ and $0 < \gamma < 1$. Therefore, the households can reduce energy usage to achieve a specific level of energy service by investing in energy efficiency. We assume that the household can use two types of energy-saving activities: efficiency investment and curtailment action. Then, the net energy-saving activity is given by the CES production function $H = (\eta K^{\rho} + (1-\eta)C^{\rho})^{\frac{1}{\rho}}$ where K is the amount of capital invested in energy efficiency and C is time spent on curtailment action. We assume $\rho \leq 1$ and $0 < \eta < 1$.

So far, we have set up the four CES functions that possess the elasticity of substitution between the two goods/inputs described by $\frac{1}{1-\alpha}$, $\frac{1}{1-\varepsilon}$, $\frac{1}{1-\sigma}$, and $\frac{1}{1-\rho}$, respectively. Although general CES functions allow α, ε, σ, and ρ to be negative and the corresponding elasticities to be less than unity, we restrict our attention to the case in which α, ε, σ, and ρ are all non-negative and the elasticities of substitution are greater than or equal to unity. Therefore, our theoretical model assumes sufficient substitutability between the two goods/inputs. However, we show that a case exists in which efficiency investment K and curtailment action C become complements.

The household faces two constraints. The first constraint is time. The household allocates total time (T) among three activities: market work (N), leisure (L), and curtailment activity (C). The time constraint can be written as

$$T = N + L + C. \tag{1}$$

The second constraint is budget. The household allocates income among three items: market goods (X), energy-efficiency capital (K), and energy (E). If the household has non labor income Ω, then the household's budget constraint becomes

$$P_X X + P_E E + P_K K = P_N N + \Omega \tag{2}$$

where P_X, P_E, P_K, and P_N are the price of the market goods, the price of energy, the price of the energy-efficiency capital, and the wage, respectively.

The household allocates time among N, L, and C and income among X, K and E, so as to maximize utility. To simplify the derivation, we solve this utility maximization problem in the order of decision making.

3.2 Allocation of Time and Income

Because of constant returns-to-scale technology of the entertainment activity, the unit cost of the entertainment activity (P_Z) depends only on two input prices (P_X and P_L). Specifically, the unit cost of the entertainment activity is defined by

$$P_Z = \left\{ \delta \left(\frac{P_X}{\delta} \right)^{\frac{\varepsilon}{\varepsilon-1}} + (1-\delta) \left(\frac{P_L}{1-\delta} \right)^{\frac{\varepsilon}{\varepsilon-1}} \right\}^{\frac{\varepsilon-1}{\varepsilon}}. \tag{3}$$

We define the cost shares of market goods X and leisure time L, respectively, which are

$$\theta_X = \frac{P_X X}{P_Z Z} = \delta \frac{\left(\frac{P_X}{\delta} \right)^{\frac{\varepsilon}{\varepsilon-1}}}{P_Z^{\frac{\varepsilon}{\varepsilon-1}}}, \qquad \theta_L = \frac{P_L L}{P_Z Z} = (1-\delta) \frac{\left(\frac{P_L}{1-\delta} \right)^{\frac{\varepsilon}{\varepsilon-1}}}{P_Z^{\frac{\varepsilon}{\varepsilon-1}}},$$

where $\theta_X + \theta_L = 1$. We later use the following properties of the unit cost function:

$$\frac{P_X}{P_Z} \frac{\partial P_Z}{\partial P_X} = \theta_X, \qquad \frac{P_L}{P_Z} \frac{\partial P_Z}{\partial P_L} = \theta_L.$$

We next focus on the energy-saving activity. With the CES production technology assumption, we define the unit cost of generating the energy-saving activity level H as

$$P_H = \left\{ \eta \left(\frac{P_K}{\eta} \right)^{\frac{\rho}{\rho-1}} + (1-\eta) \left(\frac{P_C}{1-\eta} \right)^{\frac{\rho}{\rho-1}} \right\}^{\frac{\rho-1}{\rho}}. \tag{4}$$

Since the CES production function of energy-saving activity is also characterized by constant returns-to-scale technology, the unit cost of the energy-saving activity P_H depends only on two input prices: P_K and P_C. By applying Shephard's lemma to the total cost function of the energy-saving activity ($P_H H$), we can derive the cost shares of energy-efficient investment θ_K and curtailment action θ_C:

$$\theta_K = \frac{P_K K}{P_H H} = \eta \frac{\left(\frac{P_K}{\eta}\right)^{\frac{\rho}{\rho-1}}}{P_H^{\frac{\rho}{\rho-1}}}, \qquad \theta_C = \frac{P_C C}{P_H H} = (1-\eta) \frac{\left(\frac{P_C}{1-\eta}\right)^{\frac{\rho}{\rho-1}}}{P_H^{\frac{\rho}{\rho-1}}}.$$

where $\theta_K + \theta_C = 1$. The unit cost function in Eq. (4) also carries the following properties:

$$\frac{P_K}{P_H}\frac{\partial P_H}{\partial P_K} = \theta_K, \qquad \frac{P_C}{P_H}\frac{\partial P_H}{\partial P_C} = \theta_C.$$

The unit cost of the energy service (S) is given by

$$P_S = \left\{ \gamma \left(\frac{P_H}{\gamma} \right)^{\frac{\sigma}{\sigma-1}} + (1-\gamma) \left(\frac{P_E}{1-\gamma} \right)^{\frac{\sigma}{\sigma-1}} \right\}^{\frac{\sigma-1}{\sigma}}. \tag{5}$$

We omit the proof, since its derivation is almost the same as that of P_Z. The shares of the energy cost and the energy-saving activity are

$$\theta_H = \frac{P_H H}{P_S S} = \gamma \frac{\left(\frac{P_H}{\gamma}\right)^{\frac{\sigma}{\sigma-1}}}{P_S^{\frac{\sigma}{\sigma-1}}}, \qquad \theta_E = \frac{P_E E}{P_S S} = (1-\gamma) \frac{\left(\frac{P_E}{1-\gamma}\right)^{\frac{\sigma}{\sigma-1}}}{P_S^{\frac{\sigma}{\sigma-1}}},$$

where $\theta_H + \theta_E = 1$ and the following properties can be established again:

$$\frac{P_H}{P_S}\frac{\partial P_S}{\partial P_H} = \theta_H, \qquad \frac{P_E}{P_S}\frac{\partial P_S}{\partial P_E} = \theta_E.$$

By combining Eqs. (1) and (2), the full income constraint is defined as

$$\underbrace{P_X X + P_N L}_{P_Z Z} + \underbrace{P_E E + \underbrace{P_K K + P_N C}_{P_H H}}_{P_S S} = P_N T + \Omega = Y.$$

In the case of the interior solution, $P_N = P_C = P_L$, in other words, the opportunity cost of allocating one unit of time to the energy-saving activity is the nominal wage, which is also the opportunity cost of the entertainment activity. The cost of the entertainment activity Z is $P_X X + P_N L$, which is minimized at $P_Z Z$. Meanwhile, the cost of the energy-saving activity H is $P_K K + P_N C$, which is minimized at $P_H H$. Furthermore, the cost of the energy service S is $P_E E + P_H H$, which is minimized at $P_S S$. Therefore, the household's utility maximization problem can be formulated as

$$\max_{Z,S} U = (\beta Z^{\alpha} + (1-\beta)S^{\alpha})^{\frac{1}{\alpha}}$$

subject to

$$P_Z Z + P_S S = P_N T + \Omega \equiv Y.$$

Then, we obtain the following Marshallian demand function:

$$Z = \left(\frac{P_Z}{\beta}\right)^{-\frac{1}{1-\alpha}} P^{\frac{\alpha}{1-\alpha}} Y, \qquad S = \left(\frac{P_S}{1-\beta}\right)^{-\frac{1}{1-\alpha}} P^{\frac{\alpha}{1-\alpha}} Y, \tag{6}$$

where P is the inverse of the marginal utility of income:

$$P = \left\{ \beta \left(\frac{P_Z}{\beta}\right)^{\frac{\alpha}{\alpha-1}} + (1-\beta)\left(\frac{P_S}{1-\beta}\right)^{\frac{\alpha}{\alpha-1}} \right\}^{\frac{\alpha-1}{\alpha}}. \tag{7}$$

From Eq. (6), an increase in the unit expenditure P raises both demand for the entertainment activity Z and demand for the energy service S, if the utility function is not a Cobb–Douglas type (i.e., $\alpha \neq 0$). For later use, we define expenditure shares of Z and S in the full budget Y:

$$\theta_Z \equiv \frac{P_Z Z}{Y} = \beta \frac{\left(\frac{P_Z}{\beta}\right)^{\frac{\alpha}{\alpha-1}}}{P^{\frac{\alpha}{\alpha-1}}}, \qquad \theta_S \equiv \frac{P_S S}{Y} = (1-\beta)\frac{\left(\frac{P_S}{1-\beta}\right)^{\frac{\alpha}{\alpha-1}}}{P^{\frac{\alpha}{\alpha-1}}},$$

where $\theta_Z + \theta_S = 1$. Note that the Cobb–Douglas case ($\alpha \to 0$) leads to $\theta_Z = \beta$ and $\theta_S = 1 - \beta$. The following properties of the unit expenditure function (7) are utilized in the later analysis:

$$\frac{P_Z}{P}\frac{\partial P}{\partial P_Z} = \theta_Z, \qquad \frac{P_S}{P}\frac{\partial P}{\partial P_S} = \theta_S.$$

3.3 Optimal Combinations

Since we derived the Marshallian demand of the entertainment activity Z and the energy service S, we are ready to find the derived demand for energy E, the energy-saving activity H, the energy-efficiency K, and the curtailment action C. Substituting the conditional demand, S of Eq. (6) into $E = \left(\frac{P_E}{1-\gamma}\right)^{\frac{1}{\sigma-1}} P_S^{\frac{1}{1-\sigma}} S$ and $H = \left(\frac{P_H}{\gamma}\right)^{\frac{1}{\sigma-1}} P_S^{\frac{1}{1-\sigma}} S$, we obtain

$$E = \left(\frac{(1-\gamma)(1-\beta)}{P_E}\right)^{\frac{1}{1-\sigma}} \left(\frac{P_S}{1-\beta}\right)^{\frac{\sigma-\alpha}{(1-\sigma)(1-\alpha)}} P^{\frac{\alpha}{1-\alpha}} Y, \tag{8}$$

$$H = \left(\frac{\gamma(1-\beta)}{P_H} \right)^{\frac{1}{1-\sigma}} \left(\frac{P_S}{1-\beta} \right)^{\frac{\sigma-\alpha}{(1-\sigma)(1-\alpha)}} P^{\frac{\alpha}{1-\alpha}} Y. \tag{9}$$

Similarly, substituting H of Eq. (9) into the conditional demand, $K = \left(\frac{P_K}{\eta} \right)^{\frac{1}{\rho-1}} P_H^{\frac{1}{1-\rho}} H$ and $C = \left(\frac{P_C}{1-\eta} \right)^{\frac{1}{\rho-1}} P_H^{\frac{1}{1-\rho}} H$, we obtain

$$K = \left(\frac{P_K}{\gamma(1-\beta)\eta} \right)^{-\frac{1}{1-\rho}} \left(\frac{P_H}{(1-\beta)\gamma} \right)^{\frac{\rho-\sigma}{(1-\rho)(1-\sigma)}} \left(\frac{P_S}{1-\beta} \right)^{\frac{\sigma-\alpha}{(1-\sigma)(1-\alpha)}} P^{\frac{\alpha}{1-\alpha}} Y, \tag{10}$$

$$C = \left(\frac{P_C}{\gamma(1-\beta)(1-\eta)} \right)^{-\frac{1}{1-\rho}} \left(\frac{P_H}{(1-\beta)\gamma} \right)^{\frac{\rho-\sigma}{(1-\rho)(1-\sigma)}} \left(\frac{P_S}{1-\beta} \right)^{\frac{\sigma-\alpha}{(1-\sigma)(1-\alpha)}} P^{\frac{\alpha}{1-\alpha}} Y. \tag{11}$$

3.4 Complements or Substitutes?

We then explore the complementarity between K and C. In the case of Cobb–Douglas functions (α, ρ, $\sigma \to 0$), we have $K = \gamma(1-\beta)\eta Y/P_K$ and $C = \gamma(1-\beta)(1-\eta)Y/P_C$, with $Y \equiv P_N T + \Omega = P_C T + \Omega$. Then, $\partial K/\partial P_C = 0$ and $\partial C/\partial P_K = 0$ must hold. Therefore, efficiency investment K and curtailment action C never become complements to each other. In what follows, the CES utility function is shown to be a necessary condition for the complementarity between efficiency investment K and curtailment action C. By noting $P_S = P_S(P_H, P_E)$, $P_H = P_H(P_K, P_C)$, $P_Z = P_Z(P_X, P_L)$, and $P = P(P_Z, P_S)$, cross-price differentiation of (10) and (11) yield

$$\begin{aligned} \frac{P_C}{K}\frac{\partial K}{\partial P_C} &= \frac{\rho-\sigma}{(1-\rho)(1-\sigma)}\frac{P_C}{P_H}\frac{\partial P_H}{\partial P_C} - \frac{\alpha-\sigma}{(1-\alpha)(1-\sigma)}\frac{P_C}{P_S}\frac{\partial P_S}{\partial P_C} + \frac{\alpha}{1-\alpha}\frac{P_C}{P}\frac{\partial P}{\partial P_C} + \frac{P_C}{Y}\frac{\partial Y}{\partial P_C} \\ &= \left(\psi\theta_H + \frac{\rho-\sigma}{(1-\rho)(1-\sigma)} \right)\theta_C + \frac{\alpha}{1-\alpha}\theta_Z\theta_L + \theta_T, \end{aligned} \tag{10'}$$

$$\begin{aligned} \frac{P_K}{C}\frac{\partial C}{\partial P_K} &= \frac{\rho-\sigma}{(1-\rho)(1-\sigma)}\frac{P_K}{P_H}\frac{\partial P_H}{\partial P_K} - \frac{\alpha-\sigma}{(1-\alpha)(1-\sigma)}\frac{P_K}{P_S}\frac{\partial P_S}{\partial P_K} + \frac{\alpha}{1-\alpha}\frac{P_K}{P}\frac{\partial P}{\partial P_K} \\ &= \left(\psi\theta_H + \frac{\rho-\sigma}{(1-\rho)(1-\sigma)} \right)\theta_K, \end{aligned} \tag{11'}$$

and

$$\frac{P_E}{K}\frac{\partial K}{\partial P_E} = \frac{P_E}{C}\frac{\partial C}{\partial P_E} = -\frac{\alpha-\sigma}{(1-\alpha)(1-\sigma)}\frac{P_E}{P_S}\frac{\partial P_S}{\partial P_E} + \frac{\alpha}{1-\alpha}\frac{P_E}{P}\frac{\partial P}{\partial P_E} = \psi\theta_E.$$

θ_T is the full labor income share defined as

$$\theta_T \equiv \frac{P_N T}{Y} = \frac{P_C T}{Y},$$

and ψ defined below has the same sign of $\partial K/\partial P_E$ and $\partial C/\partial P_E$:

$$\psi \equiv \frac{\alpha}{1-\alpha}\theta_S - \frac{\alpha-\sigma}{(1-\alpha)(1-\sigma)} = \frac{\sigma}{1-\sigma} - \frac{\alpha}{1-\alpha}\theta_Z.$$

When ψ is positive (negative), an increase in the energy price P_E raises (lowers) both levels of energy-efficiency investment and curtailment action.

Note that $\frac{\alpha}{1-\alpha} > 0$, $\frac{\sigma}{1-\sigma} > 0$, and $\frac{\rho}{1-\rho} > 0$ in the case in which the Cobb–Douglas functions (α, σ, $\rho \to 0$) are excluded. Therefore, ψ in the first term on the right-hand side of (10′) and (11′) is crucial for determining the sign patterns of $\partial K/\partial P_C$ and $\partial C/\partial P_K$.

Consider the effects of an increase in the cost of curtailment action P_C, which equals the increase in nominal wage P_N, on energy efficiency investment K. First, we focus on the first term in (10′) and then in (11′). An increase in curtailment action P_C directly raises P_H, which is the unit cost of energy-saving activity H. The increase in P_H further raises the cost of energy service S, that is, P_S. Under the CES utility function, the cross-price effect is present; thus, the household substitutes energy service S for entertainment activity Z and thereby the demand for energy service S becomes smaller. This also reduces the demand for energy-saving activity H and the demand for efficiency investment K. This effect brings about the complementarity between curtailment action C and efficiency investment K. The same argument holds for the first term in (11′).

The second and third terms in (10′) are both positive and explained as follows. An increase in the cost of curtailment action P_C $(= P_N)$ raises the unit costs of energy-saving activity P_H, energy service P_S, and entertainment activity P_Z, and thus, the unit expenditure P. Under CES functions, cross-price effects are present because the positive substitution effect is greater than the negative income effect. Therefore, the demand for relatively cheaper efficiency investment K increases more than the demand for more expensive curtailment action C shrinks. This saves the unit cost of energy-saving activity P_H and, thus saves subsequent unit costs of the energy service P_S, entertainment activity P_Z, and expenditure cost P. These cost-saving effects generate a positive income or output effect and thus, the demand for efficiency investment K increases. The same argument holds for the second and third terms in (11′).

The last term in (10′) is the positive income effect on the demand for efficiency investment K. An increase in the opportunity cost of curtailment action or nominal wage P_N raises the household's labor income. Consequently, the demand for efficiency investment K increases.

The condition for efficiency investment K and curtailment action C to be complements is obtained by setting $\frac{P_C}{K}\frac{\partial K}{\partial P_C} < 0$, that is,

$$\frac{\rho}{1-\rho}\theta_C + \frac{\alpha}{1-\alpha}\theta_Z\theta_L + \theta_T < \left(\frac{\alpha}{1-\alpha}\theta_Z\theta_H + \frac{\sigma}{1-\sigma}\theta_E\right)\theta_C. \tag{12}$$

This is the condition that a household decreases energy efficiency investment as the wage increases.

Note that from (10′), $\frac{P_C}{K}\frac{\partial K}{\partial P_C} < 0$ implies $\psi\theta_H + \frac{\rho-\sigma}{(1-\rho)(1-\sigma)} < -\left(\frac{\alpha}{1-\alpha}\theta_Z\theta_L + \theta_T\right)/\theta_C < 0$ and thus, from (11′), $\frac{P_K}{C}\frac{\partial C}{\partial P_K} < 0$; a household lowers the curtailment activity as the cost of energy efficiency investment decreases. If the utility function U and the production function of energy service S are both Cobb–Douglas, then both α and σ approach 0. Therefore, the inequality in (12) is never satisfied and the CES function of either U or S is a necessary condition for the complementarity of efficiency investment K and curtailment action C.

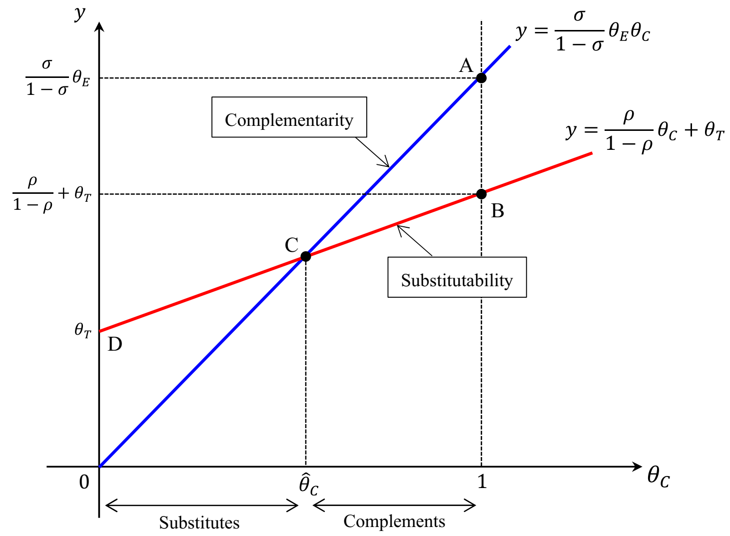

Fig. 2 Substitute or complement

On the one hand, the left-hand side of (12) has three positive terms that make efficiency investment K and curtailment action C substitutes for each other. On the other hand, the right-hand side of (12) is the driving force that makes efficiency investment K and curtailment action C complements.

We further examine the condition in (12) for the case in which U is the Cobb–Douglas utility function (i.e., $\alpha \to 0$), while S is the CES production function (i.e., $\sigma > 0$). In this case, we extract the two lines, $y = \frac{\rho}{1-\rho}\theta_C + \theta_T$ and $y = \frac{\sigma}{1-\sigma}\theta_E\theta_C$ from (12). We depict them in Fig. 2 with the horizontal axis indicating θ_C. The former is drawn as straight line BD, while the latter is straight line $A0$. When the two lines intersect at an interior point, say C, then there exists $\hat{\theta}_C \in (0, 1)$ such that efficiency investment K and curtailment action C become substitutes for $\theta_C \in (0, \hat{\theta}_C)$ and complements for $\theta_C \in (\hat{\theta}_C, 1)$, where critical value $\hat{\theta}_C$ is defined as

$$\hat{\theta}_C \equiv \frac{\theta_T}{\frac{\sigma}{1-\sigma}\theta_E - \frac{\rho}{1-\rho}}.$$

For the existence of the intersection of the two lines, point A must lie above point B, that is, $\frac{\rho}{1-\rho} + \theta_T < \frac{\sigma}{1-\sigma}\theta_E$ or, equivalently,

$$\theta_T < \frac{\sigma}{1-\sigma}\theta_E - \frac{\rho}{1-\rho}.$$

We depict the straight line $\theta_T = \frac{\sigma}{1-\sigma}\theta_E - \frac{\rho}{1-\rho}$ in Fig. 3 and the shaded area brings about the share parameters θ_T and θ_E ensuring the above inequality. From this figure, $\frac{\sigma}{1-\sigma} > \frac{\rho}{1-\rho}$ is required for the existence of the above $\hat{\theta}_C \in (0, 1)$.

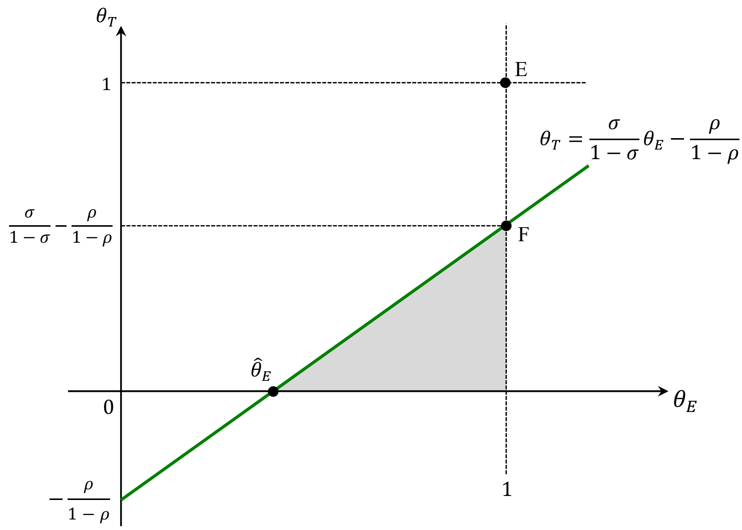

Fig. 3 Condition for the existence of $\widehat{\theta}_C$

Proposition 1 *Suppose the utility function is Cobb-Douglas* ($\alpha \to 0$), *while the production of energy service and the production of energy-saving activity are both CES with* $\frac{\sigma}{1-\sigma} > \frac{\rho}{1-\rho} > 0$. *Suppose also* $\theta_T < \frac{\sigma}{1-\sigma}\theta_E - \frac{\rho}{1-\rho}$. *Define* $\widehat{\theta}_C \equiv \theta_T / \left(\frac{\sigma}{1-\sigma}\theta_E - \frac{\rho}{1-\rho}\right)$. *Then for any* $\theta_C \in \left(\widehat{\theta}_C, 1\right)$, *energy efficiency investment and curtailment action become complements. Furthermore,* $\partial\widehat{\theta}_C / \partial\theta_T$ *is positive.*

The first condition $\frac{\sigma}{1-\sigma} > \frac{\rho}{1-\rho}$ implies that the elasticity of substitution between the energy-saving activity H and energy E is larger than the elasticity of substitution between efficiency investment K and curtailment action C. The former type of elasticity needs to be larger than the latter type to generate complementarity between efficiency investment K and curtailment action C . The second condition means that the full labor income share θ_T is sufficiently small and that the cost share of energy in energy service activity θ_E is sufficiently large. Proposition 1 states that it is necessary for the cost share of the household's energy-saving activity to be sufficiently high for complementarity to exist. For complementarity, it is also necessary for the expenditure share of the household's entertainment activity to be sufficiently high. The last part of the proposition implies that households with smaller nominal wage relative to total income are more likely to regard energy efficiency investments and curtailment actions as complements.

3.5 Joint Use of Efficiency Investment and Curtailment Action

Dividing Eq. (11) by (10), we obtain

$$C = \left[\frac{P_C}{P_K} \frac{\eta}{1-\eta} \right]^{-\frac{1}{1-\rho}} K. \tag{13}$$

Because the sign of the square bracket is positive, Eq. (13) suggests that a household that invests heavily in energy efficiency spends more time on curtailment action. In other words, the model suggests that a household uses the two types of energy-saving activities jointly and not alternatively. We examine the validity of this prediction in the following empirical section.

Governments often promote the purchase of energy-efficient products and occasionally provide subsidies for energy-efficient products to enable households to purchase them at reduced prices. Do such promotion policies lower households' curtailment action? If households use the two types of energy-saving activities alternatively, then the promotion policies would hinder voluntary curtailment actions by households. However, our result predicts the opposite. In the following empirical section, we examine the validity of this prediction by comparing curtailment actions between households that vary in the level of energy-efficiency investment.

4 Data

4.1 Survey on Carbon Dioxide Emissions from Households

The data used in this analysis are obtained from the SCDEH (Ministry of the Environment of Japan 2014, 2017, 2018). The Ministry of the Environment of Japan conducted the 2014 survey between October and September and conducted the remaining two surveys between April and March of each year. The survey uses both face-to-face and Internet surveys and includes samples of 31,133 households from all parts of Japan. The survey includes information about socioeconomic characteristics and dwelling conditions of households. It also includes information about ownership, use, and age of three types of appliances: ACs, REFs, and TVs. In this survey, the types of lights installed in the living room (incandescent, fluorescent, and LED) are also reported.

4.2 Air Conditioner

In the survey, 27,626 households with at least one AC were asked about the set temperature of their main AC. They were asked to report the set temperature between 17 and 32 °C in the survey sheet. Figure 4 shows that the distribution of the set temperature is left-skewed. Although the most popular set temperature is 27 °C, the average temperature is 26.69 °C.

In the 2014 survey, households were asked to choose the manufacturing age of their main AC from six periods: (1) before 1990, (2) 1991–1995, (3) 1996–2000, (4) 2001–2005, (5) 2006–2010, and (6) after 2010. In the 2017 and 2018 surveys, they were asked to choose the manufacturing age from six periods: (1) before 1996, (2) 1996–2000, (3) 2001–2005, (4) 2006–2010, (5) 2011–2015, and (6) after 2015. In total, 25,186 households answered the age of their main AC appropriately. If the medians of each period are used as the age of ACs, the average age of the main AC becomes 8.68 years, and the standard deviation becomes 6.60 years.

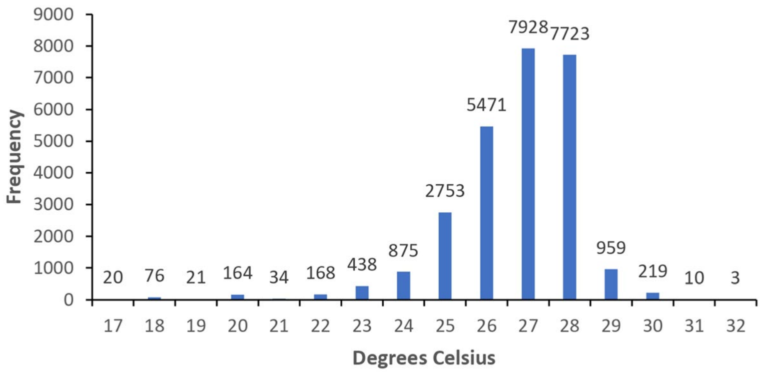

Fig. 4 AC temperature setting

The long-term use product safety labeling system demands that manufacturers display the standard usage period of their ACs, which is set at 10 years for most ACs. Therefore, we can judge that households using AC older than 10 years underinvest in energy efficiency. In the survey, approximately 30% of households answered that they still used an old AC purchased more than 10 years ago.

A household residing in a hot area is expected to set the AC temperature low. We include prefecture fixed effects to control for weather condition in the analysis. Similarly, a household residing in a hot area is expected to use ACs for longer. Therefore, we also control for time usage. Although most AC models sold in Japan have a heating function, some have only a cooling function. We exclude cooling-only modes from the dataset. A central cooling system is rarely used in Japanese households and a typical household installs ACs in some rooms. We control for the number of ACs used in a house in the analysis.

4.3 Lighting

Two type of curtailment actions related to light use were surveyed. In the first question, households were asked whether they adjust the brightness of the lighting in their home according to the situation. This adjustment includes light reduction and the use of the automatic light control function. In total, 31,047 households responded to this question. While 52.2% of households answered that they adjusted the brightness, the remaining 47.8% said that they did not. The second question asked households whether they switch off lights when leaving a room even for a short time. For this question, 31,042 households responded properly. While 78.3% of households answered that they switched off lights, the remaining 21.7% said that they did not.

In the survey, households were asked about the types of the main light used in the living room. According to the installation condition of the lights, we classify households into three types: incandescent, fluorescent, and LED. LED is most energy efficient option, lasting longer than the remaining two light types. According to the U.S. Department of Energy (2015), residential LED lighting uses at least 75% less energy and lasts 25 times longer than incandescent lighting. However, the price of LED is much higher than those of other two lights. In the analysis, we investigate whether the brightness adjustment and switch-off practice differ according to the choice of the main light.

4.4 Refrigerator

There are two questions related to REF use. In the first question, households were asked whether they adjusted the temperature setting of their REFs according to season. In the survey, 14,911 out of 30,961 households answered that they adjusted the temperature setting. Therefore, about 48.2% of households adjusted the temperature and about 51.8% did not. The second question asked households whether they avoid overstuffing their REFs, which causes cooling efficiency loss. To this second question, 7793 out of 20,566 households that replied properly answered that they avoided overstuffing. Therefore, about 66.5% of households avoided overstuffing and about 33.5% did not.

The classification of REF age is the same as that for AC age. The average year of the main AC is 9.11 years while the standard deviation is 6.38 years. Most manufacturers store REF parts for repairs only for 9 years. In addition, the Japanese government recommends that households replace their REFs about 10 years (Ministry of the Environment of Japan 2022). Nevertheless, many households continue to use old REFs. In the survey, about 32% of households answered that they were using REF produced more than 10 years ago. In the latter analysis, we examine whether temperature setting or overstuffing differ between households using REF older than 10 years and remaining households.

4.5 Television

In the SCDEH, two types of curtailment actions related to TV use were surveyed. In the first question, households were asked whether they adjusted the brightness of their TVs. In total, 30,230 households replied properly and 35.7% of them answered that they did adjust brightness. The second question asked households whether they turned off the main switch of the TV when not in use; 30,284 households replied to this question and 34.6% of them answered that they switched off the main switch.

The age of the household's main TV was surveyed. The average age of the main TV is 7.3 years while the standard deviation is 4.59. Since many households replaced their TVs when the full switch to digital broadcasting was implemented in 2011, the percentage of households using old TVs is smaller than that for ACs and REFs. In the survey, about 10% of households used TVs that were older than 10 years.

People who watch TV for long period of time might not turn off the main switch. Since the time spent watching TV may be correlated with energy-saving practice, we include the time spent watching TV in the analysis.

4.6 Other Covariates

We include household income, the number of people, the number of children, the number of seniors, and the level of homestay on weekdays. The definition and descriptive statistics of socioeconomic and housing condition variables are presented in Table 2.

4.7 Dealing with Potential Omitted Variable Bias Problems

As discussed in the introduction, households often take curtailment actions as per their usual routine. Although we consider that most variables used in the previous literature on

Table 2 Descriptive statistics of explanatory variables

	Unit	Basic model			Multivariate model		
		# households	Mean	std. dev.	# households	Mean	std. dev.
Household income[1]	1,000,000 yen	26,685	5.60	3.55	15,589	6.09	3.62
Persons	Persons	26,685	2.75	1.34	15,589	2.88	1.33
Children below 10	Persons	26,685	0.24	0.61	15,589	0.26	0.64
Seniors over 74	Persons	26,685	0.26	0.57	15,589	0.25	0.55
Homestay on weekdays[2]	Intensity: 0–3	26,685	2.05	1.21	15,589	2.07	1.20
Propensity of curtailment actions	Score: 1–5	26,685	2.57	1.26	15,589	2.71	1.23
Electricity price[3]	1000 yen	26,685	12.64	0.90	15,589	12.48	0.72
Age of house[4]	Years	26,685	22.48	14.93	15,589	20.99	14.71
Floor area	m^2	26,685	111.64	57.83	15,589	115.39	56.45
TV numbers	Number	24,584	1.98	1.07	15,589	2.06	1.11
TV use intensity[5]	Intensity: 1–8	24,584	5.92	3.74	15,589	5.91	3.71
TV investment	From om 0 to 17	24,584	16.21	2.50	15,589	16.25	2.40
AC numbers	Number	21,663	2.67	1.47	15,589	2.75	1.48
AC use intensity[6]	Intensity: 1–8	21,663	4.22	1.76	15,589	4.24	1.76
AC investment	From 0 to 17	21,663	14.91	4.06	15,589	15.01	3.94
REF numbers	Number	22,829	1.24	0.54	15,589	1.25	0.56
REF investment	From 0 to 17	22,829	14.83	3.98	15,589	15.04	3.74
LEDization share	Share	22,479	0.46		15,589	0.47	0.05

1. Household income is classified into 7 groups, and we use the median income of each group: Group 1 = 1.25, Group 2 = 3.75, Group 3 = 6.75, Group 4 = 8.75, Group 5 = 12.50, Group 6 and 7 = 17.50

2. Level of homestay on weekdays is classified into 4 levels: 0 = hardly at home, 1 = 1 or 2 days a week, 2 = 3 or 4 days a week, 3 = almost every days

3. The cost of the monthly standard usage of 441 kWh

4. The age of houses is classified into 9 levels: 1 = before 1970, 2 = 1971–1980, 3 = 1981–1985, 4 = 1986–1990, 5 = 1991–1995, 6 = 1996–2000, 7 = 2001–2005, 8 = 2006–2010, 9 = after 2011 in the 2014 survey

5. The intensity of TV use is classified into 8 levels: 1 = less than 1 h, 2 = 1–2 h, 3 = 2–4 h, 4 = 4–8 h, 5 = 8–12 h, 6 = 12–16 h, 7 = 16–20 h, 8 = more than 20 h

6. The intensity of AC use in August is classified into 8 levels: 1 = less than 2 h, 2 = 2–4 h, 3 = 4–8 h, 4 = 8–12 h, 5 = 12–16 h, 6 = 16–20 h, 7 = 20–24 h, 8 = all day

energy-saving practices are included in our empirical models, there may still be an omitted variable that is correlated with the age of appliances still. For example, there may be cases in which the ability to upgrade appliances is linked to the ability to conduct energy-saving activities. In the presence of such an omitted variable problem, we obtain a biased estimate about the effect of the investment in energy efficiency of appliances on curtailment actions.

Although one approach to deal with omitted variable bias problems is to compare energy-saving activities before and after the purchase of the new appliance, the purchase of a new appliances is an endogenous choice for each household. Therefore, the comparison of energy-saving activities before and after a new appliance purchase can cause a sample selection problem. In addition, other lifetime events can occur at the time of a new appliance purchase and it is difficult to remove the effects of such events.

An alternative approach is a randomized controlled trial (RCT). However, it would be difficult to implement an RCT for a study on the energy-saving activities of appliances, since households often have multiple appliances with a similar function and the intensity of their use varies substantially across households.

To overcome an omitted-variable bias problem, we adopt the following two approaches in this study. In addition to the curtailment actions of TV, REF, lighting, and AC use, households were asked for information on the practice of five other types of energy-saving activities in the survey. We measure the propensity for energy-saving practices of each household according to the response to the practices and then include it in the empirical model to control the habitual effect.[3] The practice of energy-saving activities captures a household's hidden preference over energy-saving but is not directly correlated with the investment level of appliances to be studied.

In the second approach, we restrict our attention to the curtailment actions of ACs, TVs, REFs, and Lights and estimate a multivariate probit model in which the seven curtailment actions are jointly modelled as a system with correlated error terms. A multivariate probit model is applicable for a range of applications whenever multiple binary decisions are involved for the same individuals (Ramful and Zhao 2009). In the present analysis, we aim to determine the common taste that households have for any pair of curtailment actions.

5 Empirical Models and Results

5.1 Basic Empirical Models

To be as consistent as possible with the theoretical model, we created the energy efficiency investment variable (K) through the following procedure. First, we standardized the energy efficiency investment level of households that answered that they were using appliances purchased more than 27 years ago to 0. Next, we increased the energy efficiency investment by one unit as the age of appliances decreases by 1 year. Finally, we assumed that households using appliances whose age was below 10 years were using appliances within the appropriate replacement cycle and applied the maximum investment level of 17. Therefore, the energy efficiency investment variable (K) is defined by the following formula.

$$K_i = \begin{cases} 27 - Age_i & if\ Age_i > 10 \\ 17 & else \end{cases}$$

Here, Age_i is the age of appliances.

In the survey, households were asked if they practiced curtailment actions for Lights, REFs, and TVs. For AC use, households were asked to choose their set temperature in a range between 17 and 32 °C. For the AC analysis, we assume that households setting AC temperature above 27 °C were taking a curtailment action.[4] We then use the following probit equation for the basic analysis:

[3] The questions are: (1) Do you set the water temperature of the warm water bidet low? (2) Do you avoid using the heating function of the toilet seat except in winter? (3) Do you turn off the power or switch to a low power mode, such as sleep mode, when not in use? (4) Do you turn off the switch of modem or router when not used? (5) Do you try not to use the heat retaining function of the rice cooker as much as possible? For each respondent, we counted the number of negative responses, such as "Although I own the corresponding home appliances, I do not take energy-saving action."

[4] The Ministry of the Environment of Japan (2020) encourages a set temperature of ACs of 28 °C or higher.

$$Curtail_i^* = \beta_0 + \beta_K K_i + \boldsymbol{\Gamma X}_i + \varepsilon_i$$
$$Curtail_i = \begin{cases} 1 & \text{if } Curtail_i^* > 0 \\ 0 & \text{if } Curtail_i^* \leq 0. \end{cases}$$

$Curtail_i^*$ is the propensity that household i takes a curtailment action. $Curtail_i$ is a binary outcome variable that takes the value of 1 if household i practiced a curtailment action and 0 otherwise. $\boldsymbol{X}_i$ is a vector of other covariates specified in Sect. 4.6. ε_i is an error term.

For the AC analysis, we further estimate a double censored tobit model, since households were asked to choose their set temperature in a range between 17 and 32 °C . Specifically, we consider the following model;

$$Temp_i^* = \beta_0 + \beta_K K_i + \boldsymbol{\Gamma X}_i + \varepsilon_i$$
$$Temp_i = \begin{cases} 17 & \text{if } Temp_i^* \leq 17 \\ Temp_i^* & \text{if } 17 < Temp_i^* < 32 \\ 32 & \text{if } Temp_i^* > 32 \end{cases}$$

where ε_i is an error term.

Although we include information about energy-saving activities as an explanatory variable, unobserved factors associated with curtailment actions may remain. In addition, previous studies report that the socioeconomic characteristics of households determine the replacement cycle of appliances (Fernandez 2000, 2001; Wang and Matsumoto 2022). These facts cast doubt on treating the energy efficiency investment as an exogenous variable. Therefore, we consider the following instrumental variable model;

$$K_i = \theta_0 + \boldsymbol{\Theta H}_i + \boldsymbol{\Phi X}_i + \omega_i,$$

where H is vector of instrumental variables. We use the age and floor area of houses as instrumental variables. Therefore, we assume that the age and floor area of a house are correlated with the age of its appliances, but are not directly correlated to the curtailment behavior.

Since the age of the lightbulbs is not investigated in the survey, we substituted the LEDization dummy into the energy efficiency investment variable (K) for the lighting analysis. This dummy variable takes a value of 1 if the household uses LED as the main light. To address the potential endogeneity of LEDization, we employed a two step estimation procedure. Therefore, we initially estimate a probit model in which the LED variable takes either 0 or 1 and then substituted the predicted LEDization probability into the energy investment (K).

The number of households that properly answered the question on curtailment actions is different and therefore, the number of samples varies between models.

5.2 Empirical Results of Basic Models

We conducted Wald tests of exogeneity for the energy efficiency investment variable and rejected the exogeneity hypothesis at the 5% level for all eight models. We also confirmed that the age and floor area of a house are strongly correlated to the energy efficiency investment variables in the first-stage analyses. We further conducted overidentification tests for all models. Since the lighting analysis did not pass the test, we used only the age of the house as an instrumental variable.

Table 3 presents the estimation results for TV, REF, Light, and AC. The first model for AC reports the result of the double censored tobit model for AC. The remaining columns

Table 3 Determinants of curtail actions (Probit model with endogenous covariates. The marginal effects show the changes in expected probability.)

	AC (N =21,663)[A]				TV (N = 24,584)				Refrigerators (N = 22,829)				Light (N = 22,479)			
	Set temperature[B]		Set temperature		Brightness adjust		Switch off		Temp adjust		Avoid overstuffing		Brightness adjust		Switch off	
	Marginal effect	Significance	Marginal effect	Significance	Marginal effect	Significance	Marginal effect	Significance	Marginal effect	Significance	Marginal effect	Significance	Marginal effect	Significance	Marginal effect	Significance
Energy efficiency investment	0.091	< 0.01	5.14%	< 0.01	22.83%	< 0.01	− 6.19%	0.02	− 2.83%	< 0.01	− 2.04%	0.01				
LED light[C]													− 12.86%	< 0.01	6.31%	< 0.01
Household income	− 1.1E−04	< 0.01	− 0.01%	< 0.01	− 1.01%	< 0.01	− 0.67%	< 0.01	− 0.81%	< 0.01	− 0.45%	< 0.01	0.34%	0.17	− 0.68%	< 0.01
Number of persons	− 0.083	< 0.01	− 7.75%	< 0.01	0.32%	0.50	0.75%	0.02	0.12%	0.71	− 3.13%	< 0.01	0.13%	0.68	0.38%	0.15
Number of children	0.005	0.82	0.03%	0.99	− 5.30%	< 0.01	0.29%	0.73	0.35%	0.69	2.31%	< 0.01	3.66%	< 0.01	− 0.78%	0.34
Number of seniors	0.026	0.19	2.42%	0.16	− 1.61%	0.11	2.07%	< 0.01	− 2.24%	< 0.01	0.56%	0.37	− 3.53%	< 0.01	3.82%	< 0.01
Stay at home on weekday	0.099	< 0.01	8.42%	< 0.01	2.11%	< 0.01	0.01%	0.96	1.35%	< 0.01	0.05%	0.84	3.73%	< 0.01	− 0.42%	0.34
Propensity to energy-saving practices	0.127	< 0.01	9.18%	< 0.01	5.66%	< 0.01	4.39%	< 0.01	7.38%	< 0.01	5.20%	< 0.01	10.26%	< 0.01	3.86%	< 0.01
Number of appliances	− 0.014	0.09	− 3.32%	< 0.01	3.28%	< 0.01	− 3.43%	< 0.01	− 2.08%	< 0.01	− 4.61%	< 0.01				
Usage of appliances	− 0.073	< 0.01	− 7.55%	< 0.01	− 1.13%	< 0.01	− 0.93%	< 0.01								
Price of electricity	1.96E−04	< 0.01	0.02%	< 0.01	4.64%	< 0.01	2.49%	< 0.01	1.18%	< 0.01	1.00%	< 0.01	4.47%	< 0.01	0.56%	0.17

Table 3 (continued)

	AC (N =21,663)[A]				TV (N = 24,584)				Refrigerators (N = 22,829)				Light (N = 22,479)			
	Set temperature[B]		Set temperature		Brightness adjust		Switch off		Temp adjust		Avoid overstuffing		Brightness adjust		Switch off	
	Marginal effect	Significance	Marginal effect	Significance	Marginal effect	Significance	Marginal effect	Significance	Marginal effect	Significance	Marginal effect	Significance	Marginal effect	Significance	Marginal effect	Significance
Wald chi2 (degree of freedom)	1547.09 (56)		1184.28 (56)		3952.22 (10)		870.3 (10)		938.77 (9)		779.65 (9)		865.15 (8)		741.74 (8)	
Prob > chi2	< 0.01		< 0.01		< 0.01		< 0.01		< 0.01		< 0.01		< 0.01		< 0.01	

A. Prefecture fixed dummies are included

B. The double censored Tobit model with endogenous covariates is used. The marginal effects are the changes in set temperature

C. The impacts of a 10% increase in LEDization probability are assessed report the results of the probit models. The marginal effects of the double-censored tobit model are the changes in the expected set temperature in terms of °C while those of the probit models are the changes in the expected probabilities (%) of the engagement in corresponding curtailment actions.

We obtained a consistent negative sign for the household income variable in all models. This result suggests that wealthy households do not take curtailment actions to lower electricity consumption. Nevertheless, the marginal effects suggest that the income effects on curtailment action are relatively small. In many cases, an income increase by 1 million yen decreases the likelihood of curtailment action less than 1%.

Households with people staying at home on weekdays are more likely to adopt energy-saving practices. This is because such households face less severe time constraints and can allocate time for energy-saving activities.

In all models, we obtain a positive sign for the variable of the propensity for energy-saving practices. This means that a person who practices energy conservation for one appliance also adopts energy-saving practices for other appliances.

The results of the analysis show that households that own multiple appliances or use them frequently do not take curtailment actions. This possibly means that such households have a strong demand for energy services for the corresponding appliances and do not pay much attention to the cost of using them.

The coefficients for electricity prices become positive in all models and statistically significant in most models. Therefore, households living in areas with high electricity prices take curtailment action more frequently.

The parameter values are different between the tobit and probit models in the AC models, because the shapes of the two models are different. However, in terms of statistical explanatory power, similar findings are obtained for both models. The set temperature becomes low if there are many family members, if family members spend more time outside the home, and if AC is used for long hours. We find that households that do not invest sufficiently in energy efficiency tend to set the AC temperature low. According to the estimation result, the probability that a household sets the AC temperature above 27 °C increases by 5.14% as the AC is replaced for 1 year. This may simply mean that households needed to set the temperature low, as the cooling performance of their old ACs had declined. However, we find no evidence of a rebound effect such that households start to pay less attention to energy consumption and reduce the set temperature after their purchase of an efficient AC.

The result shows that households with many family members are more likely to turn off the main switch of the TV when not in the use. Households with seniors are more likely to turn off the main switch while households with children are less likely to adjust TV brightness. The investment in TV efficiency is the opposite between the two curtailment actions. Households using a new TV replied that they adjusted the brightness yet turned off the main TV switch less frequently.

Households with seniors are less likely to adjust the temperature of REFs while those with children are more likely to avoid overstuffing. The empirical results shows that invest in REF's energy efficiency is negatively associated with the two curtailment actions.

The last two columns in Table 3 present the estimation results of the curtailment actions related to lighting. Brightness adjustment is carried out if there are children at home but not if there are seniors at home. The marginal effects measure the impact of a 10% increase in LEDization probability. We find that households that installed LED lighting in the living room answered that they were more careful about switching off the lights but did not adjust the brightness.

5.3 Multivariate Probit Model

In the second analysis, we estimate the multivariate probit model in which the seven curtailment actions are jointly modelled as a system with correlated error terms,

$$
\begin{gathered}
Curtail_j^* = \beta_0 + \beta \widehat{K}_j + \boldsymbol{\Gamma}_j \boldsymbol{X}_j + \varepsilon_j \\
Curtail_j = \begin{cases} 1 & \text{if } Curtail_j^* > 0 \\ 0 & \text{if } Curtail_j^* \leq 0. \end{cases} \\
j = 1, \ldots, 7
\end{gathered}
$$

where $\left(\varepsilon_1, \cdots, \varepsilon_1\right)' \sim MVN\left(0, \sum\right)$. $\widehat{K}$ is the expected investment level. The variance and covariance matrix $\sum$ is given by

$$
\sum = \begin{pmatrix} 1 & \cdots & \sigma_{71} \\ \vdots & \ddots & \vdots \\ \sigma_{17} & \cdots & 1 \end{pmatrix}
$$

where σ_{lm} is the correlation coefficient of ε_l and $\varepsilon_{,}$. A positive estimate implies that unobserved attributes that increase the likelihood of engaging in curtailment action l also increase the likelihood of engagement in curtailment action m. The parameter estimation was performed by the GHK simulation method with 100 random draws.

5.4 Empirical Results of Multivariate Probit Model

We included only households that answered the practice of all seven curtailment actions. Since some households in northern regions do not own ACs, we placed more weight on households in southern regions. Table 4 compares household characteristics used for the multivariate probit model with those used for the basic probit models.

Although we do not present the correlation matrix to save space, all the correlation coefficients become positive and statistically significant at the 1% level. Therefore, unobserved attributes that increase the likelihood of engaging in a specific curtailment action also increase the likelihood of engagement in another curtailment action.

Table 4 presents the result of the multivariate probit model. We indicate the coefficients in italics if the opposite sign to that in Table 3 is obtained. As shown, most results remain the same as those in Table 3.

The results of the multivariate probit analysis show that households that invest in energy efficiency are more likely to set the AC temperature low, adjust TV brightness, and switch off lights when not in use. We did not observe statistically meaningful results for other curtailment actions.

Our findings, which contrast those of previous studies, can be summarized as follows.

1. High income is negatively associated with curtailment actions; wealthy families do not spend time on curtailment actions.
2. The age effect depends on the type of curtailment actions; the presence of children or seniors enhances some curtailment actions but hinders others.
3. Habitual effects are strong in curtailment actions; households practicing one particular curtailment action also practice another.

Table 4 Determinants of curtail actions (Multivariate Probit model with endogenous covariates. The marginal effects show the changes in expected probability. N = 15,589)

	AC[A]		TV				Refrigerator				Light			
	Set temperature		Brightness adjust		Switch off		Temp adjust		Avoid overstuffing		Brightness adjust		Switch off	
	Marginal effect	Significance	Marginal effect (%)	Significance	Marginal effect (%)	Significance	Marginal effect (%)	Significance	Marginal effect (%)	Significance	Marginal effect (%)	Significance	Marginal effect (%)	Significance
Energy efficiency investment	2.28%	< 0.01	9.92	< 0.01	− 0.82	0.77	*0.60*	0.56	− 0.39	0.69				
LED light[B]											*1.66*	0.94	6.82	< 0.01
Household income	− 0.36%	< 0.01	− 0.43	< 0.01	− 0.59	< 0.01	− 0.69	< 0.01	− 0.33	< 0.01	*− 0.44*	0.04	− 0.47	0.01
Number of persons	− 3.08%	< 0.01	0.13	0.75	0.91	0.02	0.13	0.74	− 3.33	< 0.01	0.18	0.64	0.44	0.16
Number of children	*− 0.72%*	0.428	− 1.86	0.04	*− 0.40*	0.65	*− 1.87*	0.066	1.39	0.14	− 0.03	0.98	− 1.11	0.19
Number of seniors	0.55%	0.454	− 3.49	< 0.01	1.20	0.12	− 2.84	< 0.01	0.29	0.69	− 0.92	0.40	3.33	< 0.01
Stay at home on weekday	2.96%	< 0.01	1.59	< 0.01	0.44	0.20	1.77	< 0.01	0.46	0.16	2.18	< 0.01	− 0.37	0.43
Propensity to energy-saving activities														
Number of appliances	− 0.39%	0.176	2.64	< 0.01	− 2.30	< 0.01	− 0.35	0.63	− 3.15	< 0.01				
Usage of appliances	− 2.23%	< 0.01	− 0.70	< 0.01	− 0.87	< 0.01								
Price of electricity	7.37%	< 0.01	3.65	< 0.01	3.08	< 0.01	2.44	< 0.01	1.10	0.04	3.78	< 0.01	0.86	0.13

Table 4 (continued)

	AC[A]		TV				Refrigerator				Light			
	Set temperature		Brightness adjust		Switch off		Temp adjust		Avoid overstuffing		Brightness adjust		Switch off	
	Marginal effect	Significance	Marginal effect (%)	Significance	Marginal effect (%)	Significance	Marginal effect (%)	Significance	Marginal effect (%)	Significance	Marginal effect (%)	Significance	Marginal effect (%)	Significance
Wald chi2 (degree of freedom)	1360.04 (103)													
Prob > chi2	< 0.01													

A. Prefecture fixed dummies are included

B. The impacts of a 10% increase in LEDization probability are assessed

4. Time constraint affects curtailment actions; households engage in curtailment actions more frequently if their family members stay at home in the daytime on weekdays.
5. Households that invest in energy efficiency adopt curtailment actions more frequently than households that do not invest in energy efficiency.

6 Conclusion and Policy Implications

To save energy, a household invests in energy efficiency and simultaneously takes curtailment action. However, previous studies have analyzed the use of two energy-saving activities separately. To find effective energy policies in the residential sector, it is necessary to understand how a household uses these two measures. In this study, we developed an energy-saving model based on the household production framework and analyzed how a household uses the two energy-saving measures. If energy-saving products become available at lower cost, we expect a household to increase efficiency investment and to reduce curtailment action. However, we show that a household does not necessarily reduce curtailment action when a time allocation problem arises between energy-saving and other entertainment activities. If the price of energy-efficient products decreases, the energy service becomes available at lower cost. Hence, the energy service becomes more attractive than the entertainment activity. Therefore, a household re-allocates time from entertainment activity to curtailment action.

Since efficiency investment and curtailment action can be either complements or substitutes, it is important to know how households' curtailment action is associated with their efficiency investment decisions. Our empirical analysis reveals that a household investing in energy efficiency of appliances is more likely to take the curtailment actions. The result predicts that curtailment action is not discouraged by the promotion of energy-efficient products. Our results suggest that government policies to promote energy-efficient products do not crowd out households' curtailment action.

Our empirical analysis shows that personality type influences energy-saving actions greatly. Households that do not invest in energy saving do not practice energy saving. Those that continue to use old appliances do not know the energy efficiency of their appliances and do not take curtailment action. In summary, they pay less attention to electricity consumption. It is necessary to implement policies that encourage people with less awareness of energy saving to invest in energy efficiency. One such policy is a scrap incentive program for households that replace an old appliance with a new one. Another is a differentiated recycling fee according to the age of appliances.

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