TCER Working Paper Series

Efficiency investment and curtailment action: complements or substitutes

Shigeru Matsumoto
Hajime Sugeta

August 2019

Working Paper E-137
http://tcer.or.jp/wp/pdf/e137.pdf

TOKYO CENTER FOR ECONOMIC RESEARCH
1-7-10-703 Iidabashi, Chiyoda-ku, Tokyo 102-0072, Japan

Abstract

Households. energy-saving activities are often categorized into efficiency investment and curtailment action. Although households use these two activities simultaneously, previous studies have analyzed these two activities separately. In this study, we develop an energy-saving model based on a household production framework to show how these two activities are related. We assume that a household allocates time among market work, leisure, and curtailment action. We further assume that the household spends income on purchasing market goods, energy efficiency investment, and energy service. The household receives utility from entertainment activity and energy service but both market goods and leisure time are necessary for entertainment activity. If the household spends time on curtailment action, then leisure time form entertainment activity will be reduced. In contrast, if the household spend money for efficiency investment, then market goods available for entertainment activity will be reduced. With this household production framework, we show that a household can use energy efficiency investment and curtailment action jointly; namely, a household who invest heavily in energy efficiency will spend more time on curtailment action. In the empirical section, we use microlevel data from the Survey on Carbon Dioxide Emission from Households (SCDEH) to examine the validity of this prediction in a real world setting. SCDDH contains a wide variety of information related to household's energy usage, and both curtailment actions of households and vintage of appliances that households own were surveyed. Using this information, we examine whether the intensity of curtailment action varies between households owning new and old appliances. We show that households using an old television (TV) turn o¤ the main switch of TV more frequently but those using a new refrigerator (REF) adjust the temperature according to the season and avoid overstuffing to maintain cooling efficiency. Furthermore, we show that households installing light emitting diode (LED) lamps control brightness of rooms and those using a new air conditioner (AC) set room temperature higher. Therefore, we observe that respondents jointly use efficiency investment and curtailment action, except in the case of a TV switch-off. This result predicts that the promotion of energy saving products will not hinder the households' voluntary energy saving practice.

Shigeru Matsumoto
TCER
and
Aoyama Gakuin University
Economics
1508366
shmatsumoto@aoyamagakuin.jp

Hajime Sugeta
Kansai University
Economics
5648680
sugeta@kansai-u.ac.jp

Efficiency investment and curtailment action: complements or substitutes

Shigeru MATSUMOTO*and Hajime SUGETA†

This Version 27 AUG 2019

Abstract

Households' energy-saving activities are often categorized into efficiency investment and curtailment action. Although households use these two activities simultaneously, previous studies have analyzed these two activities separately. In this study, we develop an energy-saving model based on a household production framework to show how these two activities are related. We assume that a household allocates time among market work, leisure, and curtailment action. We further assume that the household spends income on purchasing market goods, energy efficiency investment, and energy service. The household receives utility from entertainment activity and energy service but both market goods and leisure time are necessary for entertainment activity. If the household spends time on curtailment action, then leisure time form entertainment activity will be reduced. In contrast, if the household spend money for efficiency investment, then market goods available for entertainment activity will be reduced. With this household production framework, we show that a household can use energy efficiency investment and curtailment action jointly; namely, a household who invest heavily in energy efficiency will spend more time on curtailment action. In the empirical section, we use microlevel data from the Survey on Carbon Dioxide Emission from Households (SCDEH) to examine the validity of this prediction in a real world setting. SCDDH contains a wide variety of information related to household's energy usage, and both curtailment actions of households and vintage of appliances that households own were surveyed. Using this information, we examine whether the intensity of curtailment action varies between households owning new and old appliances. We show that households using an old television (TV) turn off the main switch of TV more frequently but those using a new refrigerator (REF) adjust the temperature according to the season and avoid overstuffing to maintain cooling efficiency. Furthermore, we show that households installing light emitting diode (LED) lamps control brightness of rooms and those using a new

*Department of Economics, Aoyama Gakuin University. Room 828, Building 8, 4-4-25 Shibuya, Shibuya, Tokyo, 150-8366. *E-mail address:* shmatsumoto@aoyamagakuin.jp.

†Department of Economics, Kansai University. 3-3-35 Yamate-cho, Suita, Osaka, 564-8680. *E-mail address:* sugeta@kansai-u.ac.jp.

air conditioner (AC) set room temperature higher. Therefore, we observe that respondents jointly use efficiency investment and curtailment action, except in the case of a TV switch-off. This result predicts that the promotion of energy saving products will not hinder the households' voluntary energy saving practice.

- **Key words:** 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 energy efficiency in energy-consuming products. At the same time, they have promoted energy-efficient products to households. By investing in energy efficiency of energy-consuming products, households can lower the effective price of energy service and thus can reduce energy consumption without lowering energy service level. However, households need to incur additional expenses to install new energy-efficient products since the prices of the products are more expensive than those of conventional products.

Households have taken curtailment actions such as turning off unused lights and unplugging charging devices for a long time. In recent years, power companies have introduced various experimental behavioral programs to change 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 in the program, they instead need to spend time.

Thus, households can use two types of energy-saving activities: efficiency investment and curtailment action. While money becomes a crucial factor in efficiency investment, time often becomes a crucial factor in curtailment action. Since the relative importance of money and time varies between households (Gronau and Hamermesh 2006; Gronau and Hamermesh 2008), it is natural to expect that the optimal combination of efficiency investment and curtail action will vary between households. How the optimal combination of efficiency investment and curtailment action is related? Will households lower curtailment action when the price of energy-efficient product decreases? Will households no longer practice energy-saving activities after purchasing new energy-saving products? To answer these questions, we develop 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 a household works longer hours outside and spends more time on leisure, it can enjoy entertainment activity more. However, it needs to cut back time on curtailment action and needs to pay higher energy bill. Instead of spending time on curtailment action, a household can purchase energy-efficieny products. Although the household can lower the effective price of energy service through the energy efficiency investment, they need to reduce the amount of market goods purchased. The household's energy-saving activity is characterized by a production function of two inputs: efficiency investment and curtailment action. With this household production framework, we obtain the following theoretical findings.

We show that efficiency investment and curtailment action become substitutes if household's utility is given by a Cobb-Douglas function. In contrast, efficiency investment and curtailment action can become either complements or substitutes, if household's utility is given by a 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 two energy-saving measures. However, the price increase of energy-efficient products makes energy-saving activities more costly and thus the cost of energy service becomes higher, comparing to the one of entertainment activity. Consequently, the household reduces energy service consumption and increases entertainment activity. This second cross-price effect lowers the energy saving activity and thus time 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 the paper, 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 an empirical study, instead of investigating how the price change in energy-efficient products affects energy-saving practice, we examine the relationship between efficiency investment and curtailment action directly. For this purpose, we analyze microlevel data from the Survey on Carbon Dioxide Emission from Households (SCDEH) (Ministry of the Environment of Japan (MOEJ) 2016). In SCDEH, households are asked about their energy saving practices together with the vintage of their electric appliances. After controlling socio-economic variables, we examine whether households who own new appliances practice energy saving less or more actively.[1] Our empirical results reveal that households using an old Television (TV) turn off the main switch of TV more frequently but those using a new refrigerator (REF) adjust the temperature according to seasons and avoid overstuffing to maintain cooling efficiency. Furthermore, we found that households installing light emitting diode (LED) lamps control brightness of the room and those using a new air conditioner (AC) set room temperature higher. Therefore, we found that the household uses efficiency investments and curtailment actions jointly, except in the case of a TV switch-off.

We believe our empirical finding provides an important implication for energy policy. As mentioned earlier, many governments have implemented policies

[1]Although the vintage of appliances is not perfectly correlated with the energy efficiency of appliances, previous studies often use it as a proxy of energy efficiency (Rapson 2014; Tsvetanov and Segerson 2014).

to promote energy-consuming products. If households weaken curtailment actions after purchasing energy-efficient products, then such promotion policies will crowd out voluntary energy-saving behavior by households. In contrast, the complementary relationship found in this study suggests that governments can promote energy-efficient products without concerning about crowding-out problems.

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

2 Literature review

Researchers have classified energy saving measures from various viewpoints. For example, Boudet (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. Then, they 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 classification would be the classification between energy investment and curtailment action (Karlin et al. 2012). Curtailment actions are conducted as habitual and daily practices and do not require much financial resources. Those actions include energy saving actions such as turning off the lights in empty rooms, adjusting the temperature appropriately, and avoiding over stuffing in the refrigerator. On the other hand, efficiency investments are non-routine activities and require financial resources. Energy saving investments include replacement of home appliances and housing renovation.

Using microlevel data, researchers have been analyzing household energy saving behaviors. Earlier studies have focused on the market failure 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 the 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. Reduced-form logit models have been estimated 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 microlevel 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 energy bill. Hence, they confirmed that households did not take energy-saving actions if they do not have to pay energy bill by themselves. They 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 for many US apartments. Levinson and Niemann (2014) used the US data from the Residential Energy Consumption Survey (RECS) and the American Housing Survey, to provide the explanation about this market failure. Although rents of the apartment including energy costs are higher than those of comparable metered apartments, the difference in rents is relatively small. Based on this empirical finding, the authors argue that the market failure is observed because the landlords value the contracts more than the cost of that extra energy.

In recent years, researchers have been analyzing the determinants of both efficiency investments and curtailment actions. Urban and Ščasny (2012) used the data of 9242 households from the survey conducted in 10 OECD countries in 2008, and estimated a structural equation model in order to examine how socioeconomic characteristics and environmental attitudes of households affect 5 curtailment actions and 5 efficiency investments. They confirmed that (1) age positively affects both curtailment actions and efficiency investments, (2) income has a positive impact on efficiency investments while it has a negative impact on curtailment actions. In addition, they reported that education and gender have no strong impact, and that large households invest in energy efficiency.

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

Mills and Schleich (2012) investigate 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 (REMODECE) survey conducted in 10 EU countries and Norway. As for energy efficiency investments, factor analysis was conducted based on the holding status of energy efficient products related to refrigerators, freezers, dishwashers, washing machines, dryers, office equipment, and lighting. On the other hand, 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; 6) setting energy saving features on the computer desktop. They reported that households with young children are more likely to invest energy efficiency and take curtailment actions. Furthermore, they also 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 next year after the Tohoku Great Earthquake for about 1000 households living in Kanagawa prefecture, Japan. Although he found that women actively practiced energy saving behaviors, he did not find the effect of income and age. He further observed social interactions about energy saving practice and argued that it would be effective to provide information about energy saving measures to those who actively interact with others outside 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 impact on neither temperature settings nor 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 the 2009-10 energy saving survey on lighting, TVs, refrigerators and air conditioners in five Asian cities (Dalian, Chongqing, Fukuoka, Bangkok, Ho Chi Minh), and compared the determinants of energy saving behaviors across countries. They confirmed that interest in global warming problem, environmental behavior, and social connections had a strong influence on energy-saving behaviors. They also confirmed that income and age had a weak positive impact on energy-saving behaviors. Although their research has the strength on international comparison, it has a weakness on the preciseness since energy-saving behaviors is less specific.

Traynor et al. (2014) used microlevel data of about 6000 households from the 2008-09 British Household Panel Survey (BHPS) conducted to investigate whether those who state that energy saving is important for global environmental problem take energy saving behaviors at home. They studied heating expense since it is less likely to be checked by outsiders. They found that (1) high-income households spend more for heating, (2) there is an inverse U-shaped relationship between age and heating expenses, (3) neither number of children nor employment status has effects on heating expense. Although general concern about environmental problems has no influence on heating costs, households taking pro-environmental behaviors in daily life consume less energy. In addition, households who think that time required for pro-environmental behaviors is relatively small 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. They further found that the effect of these attitudes and behaviors is maintained regardless of income level. Given these empirical observations, they reject the green hypocrisy hypothesis; people having the strong attitude toward 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. They found that people who keep postponing planned tasks or decision engage in neither curtailment actions nor efficiency investments. In addition, they found the evidence about so-called low cost hypothesis, namely people with high environmental awareness engage in low-cost curtailment actions but do not necessarily engage in high-cost energy invests. They reported several findings: (1) income has a positive effect on efficiency investments but has a negative effect on curtailment actions; (2) education has a positive effect on curtailment actions but has no effect on efficiency investments; (3) young people do not take curtailment actions; (4) women are less active on efficiency investments.

Botetzagias et al. (2014) conducted original survey on 285 Greek households to find out the determinants of the 7 curtailment actions: (1) switch off all light when leaving a room as last person, (2) set the washing machine's temperature at 60°C instead of 90°C, (3) the washing machine when it is not completely full, (4) switch off the TV when nobody watches it, (5) switch off the computer when it is not used, (6) switch off stand by when electric devices are not used, (7) put a lid on the pot when boiling food. They confirmed that different energy saving behavior was decided by different factors. However, they have also 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 Social Survey, Households and the Environment. They found that pro-environmental households would invest in energy efficiency (purchase of energy-efficient appliances, double window, energy saving light bulbs) and would take curtailment action (temperature control) more frequently. In contrast, they found that households' willingness to pay for environmental protection has no influence on energy-saving behaviors. They further found the evidence about low-cost hypothesis; pro-environmental households don't invest in energy efficiency when investment costs are high. In addition, they obtained the following results. 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 conducted in 2014, Belaid and Garcia (2016) estimate the individual's "energy saving ability" from multiple energy saving practices based on Item Response Theory. Then, they use Lasso to identify the determinants of energy saving ability. They confirmed that (1) higher energy price promotes energy saving behavior, (2) people living in the less energy efficient house take energy saving behavior, and (3) there is a U-shaped relationship between age and energy saving behavior. On the other hand, they found that income and education do not have an impact on energy ability.

Using the data from 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 are estimated by three separate equations. They classified six types of curtailment actions based on the principal component analysis. Subsequently, they study the effect of socio-economic characteristics, housing characteristics, and environmental attitudes of the subject on three energy-saving behaviors. They found that (1) environmental attitudes influence both curtailment actions and purchase of energy efficient appliances, however do not influence housing renovations, (2) income and housing characteristics have very different impacts between curtailment actions and housing renovation.

Table 1. Empirical findings from previous studies

Study	Region or country	Year	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 27000	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 Ščasný (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

In this section, we reviewed the studies that evaluated energy saving behaviors (curtailment actions and efficiency investments) based on the analysis of microlevel 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-shape relationship with curtailment actions.

3. Some scholars have a positive impact of education 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 the persons taking energy saving behaviors. More importantly, there are no study that considered the simultaneous use of curtailment actions and efficiency investments. Even in the studies analyzing 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 Figure 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 Cobb-Douglas production function $Z = X^{\delta} L^{1-\delta}$ where $0 < \delta < 1$. If the household engages in energy-saving activity H and consumes energy E, then it receives energy service $S = H^{\gamma} E^{1-\gamma}$ where $0 < \gamma < 1$. Therefore, the households can reduce the energy to achieve the 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 for curtailment action. We assume $\rho \leq 1$ and $0 < \eta < 1$.

The household faces the two constraints. The first constraint the is time constraint. 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

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

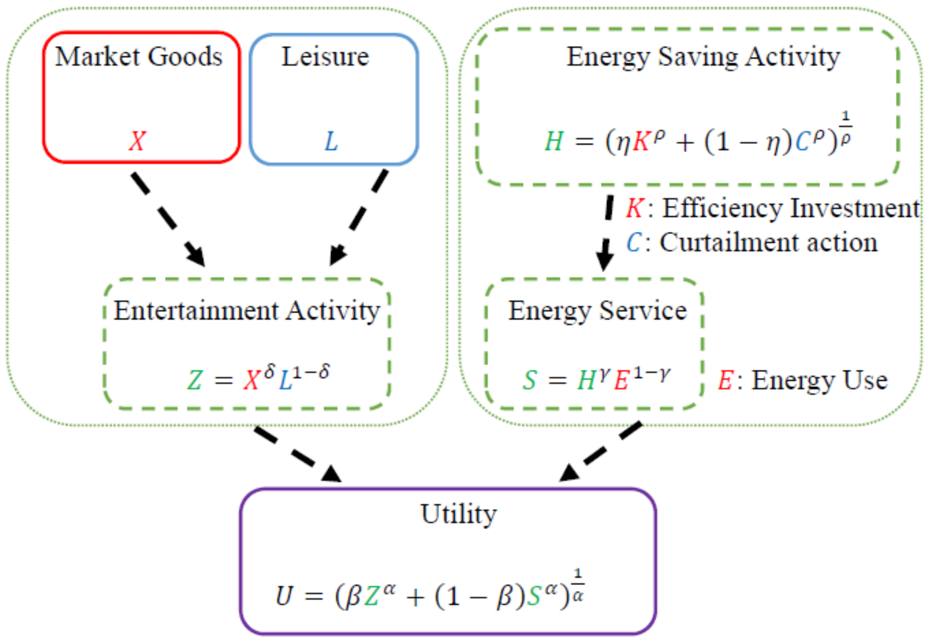
The second constraint is the budget constraint. The household allocates income among three items: market goods (X), energy-efficiency capital (K), and energy (E). If the household has non labor income Ω, then the household's budget constrain becomes

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

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. In order to simplify the derivation, we solve this utility maximization problem in the order of decision making.

Figure 1. Structure of household production model



Black: Exogenous variables
Green: Endogenous variables

Time constraint: $T = N + L + C$
Blue: choice variables related to time constraint

Budget constraint: $P_X X + P_K K + P_E E = N + \Omega$
Red: choice variables related to budget constraint

3.2 Allocation of time and income

Because of constant-regurns-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

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

Proof. See Appendix 1 for the derivation. ■

It should be noted that due to the Cobb-Douglas specification, δ and $1-\delta$ can be interpreted as the cost shares of market goods X and leisure time L, respectively. Those are

$$\delta = \frac{P_X X}{P_Z Z}, \qquad 1-\delta = \frac{P_L L}{P_Z Z}.$$

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

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

Proof. See Appendix 2 for the derivation. ■

Since the CES production function of energy-saving activity is also characterized by constant-regurns-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;

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

where $\theta_K + \theta_C = 1$.

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

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

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

$$\gamma = \frac{P_H H}{P_S S}, \qquad 1-\gamma = \frac{P_E E}{P_S S}.$$

By combining Equations (1) and (2), the full income constraint is defined by

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

In the case of interior solution, $P_N = P_C = P_L$, i.e., the opportunity cost of allocating one unit of time on 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 $P_Z Z$. On the other hand, 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 demands:

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

where P is the marginal utility of income:

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

Proof. See Appendix 3 for the derivation. ■

In view of the Equation (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 budeget 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 $\theta_S = 1 - \beta$.

3.3 Optimal combinations

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

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

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

Similarly, substituting for H of the Equation (9) into the conditional demands, $K = \left(\frac{P_K}{\eta}\right)^{\frac{1}{\rho-1}} P_H^{\frac{1}{1-\rho}} H$ and $C = \left(\frac{P_C}{1-\eta}\right)^{\frac{1}{\rho-1}} P_H^{\frac{1}{1-\rho}} H$, we get

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

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

Proof. See Appendix 4 for the derivation of these derived demands. ■

3.4 Complenets or substitutes

We then explore the complementarity between K and C. In the case of Cobb-Douglas functions ($\alpha,\ \rho \to 0$), we have $K = \delta\gamma(1-\beta)\eta Y/P_K$ and $C = \delta\gamma(1-\beta)(1-\eta)Y/P_C$, 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 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 differentiations of (10) and (11) tell us

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

$$\begin{aligned}
\frac{P_K}{C}\frac{\partial C}{\partial P_K} &= -\frac{\alpha}{1-\alpha}\frac{P_K}{P_S}\frac{\partial P_S}{\partial P_K} + \frac{\rho}{1-\rho}\frac{P_K}{P_H}\frac{\partial P_H}{\partial P_K} + \frac{\alpha}{1-\alpha}\frac{P_K}{P}\frac{\partial P}{\partial P_K} \\
&= \left(-\frac{\alpha}{1-\alpha}\gamma\theta_Z + \frac{\rho}{1-\rho}\right)\theta_K. \quad (11')
\end{aligned}$$

θ_T is the full labor income share defined as

$$\theta_T \equiv \frac{P_N T}{Y}.$$

Note that $\frac{\alpha}{1-\alpha} > 0$ and $\frac{\rho}{1-\rho} > 0$ in the case where the Cobb-Douglas functions (α, $\rho \to 0$) are excluded. The first term in each above expression is therefore crucial to 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 is equal to 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, i.e., P_S. Under the CES utility function, the cross-price effect is present and thus the household substitutes energy service S for entertainment activity Z and thus the demand for energy service S becomes smaller. It reduces the demand for energy-saving activity H and the demand for efficiency investment K as well. This effect brings about the complementarity between curtailment action C and efficiency investment K. The same argument is valid to 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 energy-saving activity P_H, energy service P_S, and entertainment activity P_Z and thus the unit expenditure P. Under CES functions, the 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 expands 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 the subsequent unit costs of energy service P_S, entertainment activity P_Z, and the expenditure cost P. These cost saving effects creates the positive income or output effect and thus the demand for efficiency investment K expands. The same argument is valid to 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 curtailment action P_C or nominal wage P_N means an increase in nominal wage and thus it raises the household's labor income. As a consequence, the demand for efficiency investment K expands.

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

$$\frac{\alpha}{1-\alpha}(1-\delta)\theta_Z + \frac{\rho}{1-\rho}\theta_C + \theta_T < \frac{\alpha}{1-\alpha}\gamma\theta_C\theta_Z. \tag{12}$$

Note that (12) implies $-\frac{\alpha}{1-\alpha}\gamma\theta_Z + \frac{\rho}{1-\rho} < -\left(\frac{\alpha}{1-\alpha}(1-\delta)\theta_Z + \theta_T\right)/\theta_C < 0$ and thus $\frac{P_K}{C}\frac{\partial C}{\partial P_K} < 0$. If the utility function is Cobb-Douglas, then α approaches to 0. Therefore, the inequality in (12) is never satisfied and the CES utility function is a necessary condition for the complementarity of efficiency investment K and curtailment action C.

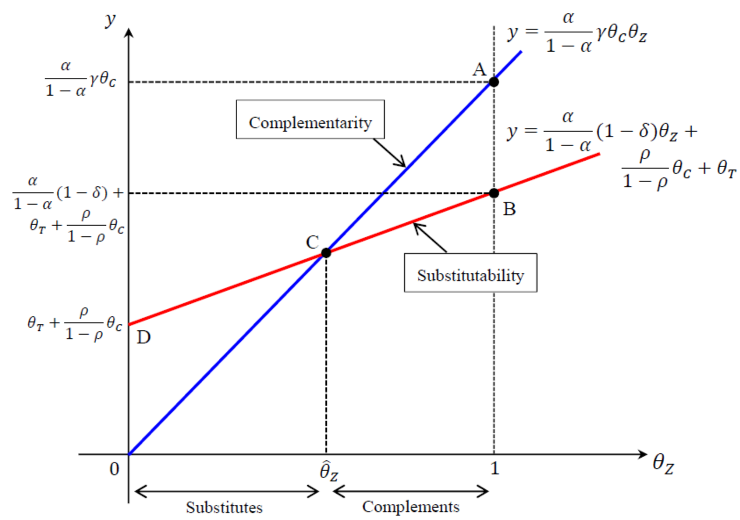


Figure 2. Substitute or Complement

The left-hand side of (12) has positive three terms that make efficiency investment K and curtailment action C substitutes 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), from which we extract the two lines, $y = \frac{\alpha}{1-\alpha}(1-\delta)\theta_Z + \frac{\rho}{1-\rho}\theta_C + \theta_T$ and $y = \frac{\alpha}{1-\alpha}\gamma\theta_C\theta_Z$ and we depict them in Figure 2 with the horizontal axis indicating θ_Z. 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 point C, then there exists $\widehat{\theta}_Z \in (0,1)$ such that efficiency investment K and curtailment action C become substitutes for $\theta_Z \in \left(0, \widehat{\theta}_Z\right)$ and complements for $\theta_Z \in \left(\widehat{\theta}_Z, 1\right)$, where critical value $\widehat{\theta}_Z$ is defined as

$$\widehat{\theta}_Z \equiv \frac{\frac{\rho}{1-\rho}\theta_C + \theta_T}{\frac{\alpha}{1-\alpha}(\gamma\theta_C - 1 + \delta)}, \qquad \text{with } \theta_C > \frac{1-\delta}{\gamma} \text{ and } \gamma > 1-\delta.$$

For the existence of the intersection of the two lines, it is required that point A must lie above point B, i.e.,

$$\frac{\alpha}{1-\alpha}(1-\delta) + \frac{\rho}{1-\rho}\theta_C + \theta_T < \frac{\alpha}{1-\alpha}\gamma\theta_C.$$

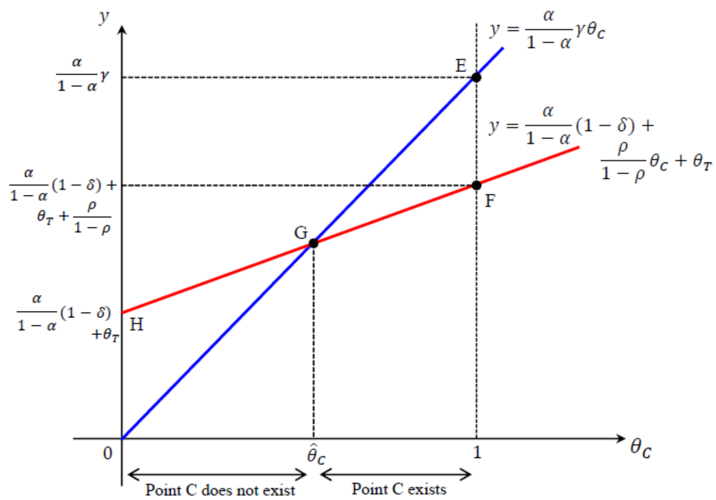


Figure 3. Condition for the existence of $\hat{\theta}_Z$

Similarly, we draw two lines, $y = \frac{\alpha}{1-\alpha}(1-\delta) + \frac{\rho}{1-\rho}\theta_C + \theta_T$ and $y = \frac{\alpha}{1-\alpha}\gamma\theta_C$ in Figure 3 with the horizontal axis indicating θ_C. When the two line intersect at an interior point G, then there exists $\widehat{\theta}_C \in (0,1)$ such that for $\theta_C \in \left(\widehat{\theta}_C, 1\right)$, point C is realized, where critical value $\widehat{\theta}_C$ is defined as

$$\widehat{\theta}_C \equiv \frac{\frac{\alpha}{1-\alpha}(1-\delta) + \theta_T}{\frac{\alpha}{1-\alpha}\gamma - \frac{\rho}{1-\rho}}, \qquad \text{with } \gamma > \frac{\frac{\rho}{1-\rho}}{\frac{\alpha}{1-\alpha}} \text{ and } \frac{\alpha}{1-\alpha} > \frac{\rho}{1-\rho}.$$

For the existence of such $\widehat{\theta}_C$, the following inequality must hold:

$$\frac{\alpha}{1-\alpha}(1-\delta) + \frac{\rho}{1-\rho} + \theta_T < \frac{\alpha}{1-\alpha}\gamma$$

or, equivalently,

$$\theta_T < \frac{\alpha}{1-\alpha}\left(\gamma + \delta - 1 - \frac{\rho}{1-\rho}/\frac{\alpha}{1-\alpha}\right).$$

Note first that $\gamma+\delta$ must be restricted by $0 < \gamma+\delta < 2$. If $\gamma+\delta < 1+\frac{\rho}{1-\rho}/\frac{\alpha}{1-\alpha}$, then the right-hand side of this inequality becomes negative and thus $\theta_T < 0$ is obtained. This contradicts $\theta_T > 0$. Hence $\gamma + \delta > 1 + \frac{\rho}{1-\rho}/\frac{\alpha}{1-\alpha}$ is required for the existence of $\widehat{\theta}_C \in (0,1)$.

Proposition 1 *Suppose $\gamma + \delta > 1 + \frac{\rho}{1-\rho}/\frac{\alpha}{1-\alpha}$ and $\frac{\alpha}{1-\alpha} > \frac{\rho}{1-\rho}$. Define $\widehat{\theta}_C \equiv \frac{\frac{\alpha}{1-\alpha}(1-\delta)+\theta_T}{\frac{\alpha}{1-\alpha}\gamma - \frac{\rho}{1-\rho}}$. For any $\theta_C \in \left(\widehat{\theta}_C, 1\right)$, define next $\widehat{\theta}_Z \equiv \frac{\frac{\rho}{1-\rho}\theta_C + \theta_T}{\frac{\alpha}{1-\alpha}(\gamma\theta_C - 1 + \delta)}$. Then for* *any* $\theta_Z \in \left(\widehat{\theta}_Z, 1\right)$*, efficient energy investment and curtailment action become complements. Furthermore,* $\partial\widehat{\theta}_C/\partial\theta_T$ *and* $\partial\widehat{\theta}_Z/\partial\theta_T$ *are both positive.*

The term $\gamma + \delta$ in the first condition jointly measures the importance of the household's energy saving activity H and the general goods X. The second condition $\frac{\alpha}{1-\alpha} > \frac{\rho}{1-\rho}$ implies the elasticity of substitution between the entertainment activity Z and the energy service S is larger than that of substitution between efficiency investment K and curtailment action C. The former elasticity needs to be larger than the latter one to generate the complementarity between efficiency investment K and curtailment action C. The above proposition states that the cost share of the household's energy saving activity is necessary to be sufficiently high for the complementarity. It also requires for the complementarity that the expenditure share of the household's entertainment activity is necessary to be sufficiently high. The last part of the proposition implies that when households with the smaller nominal wage relative to total income are more likely to regard efficient energy investments and curtailment actions as complements.

Dividing Equation (11) by Equation (10), we have

$$C = \left[\frac{P_C}{P_K}\frac{\eta}{1-\eta}\right]^{\frac{1}{1-\rho}} K. \tag{12}$$

Because the sign of the square bracket is positive, Equation (12) suggests that a household who invests heavily in energy efficiency spends more time on curtailment action. In other words, this model suggests that a household uses two types of energy-saving activities jointly and not alternatively. We will examine the validity of this prediction in the following empirical section.

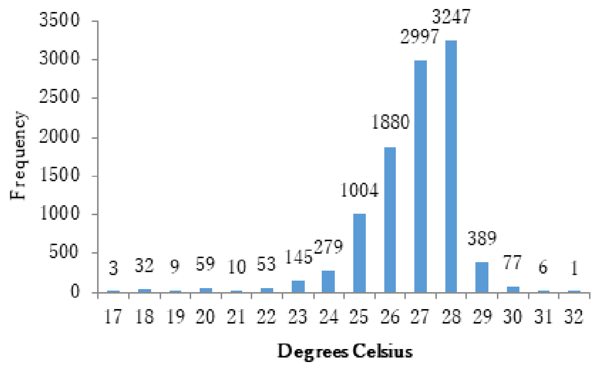
Governments occasionally provide subsidies to energy-efficient products to enable households purchase them at reduced prices. Do such promotion policies lower households' curtailment action? The opportunity cost of curtailment action increases as the wage increases. Does the wage increase enhances the efficiency investment always? Using the derivation results, we will examine whether efficiency investment and curtailment action are substitutes or complements.

4 Data

4.1 Survey on Carbon Dioxide Emission from Households (SCDEH)

The data used in this analysis are obtained from the SCDEH (MOEJ, 2016). The SCDEH is a survey conducted by the Ministry of the Environment of Japan (MOEJ) between October 2014 and September 2015. It uses both in-person and Internet surveys and includes samples of 11,632 households from all parts of Japan. The survey includes information about socioeconomic characteristics

Figure 4. AC temperature setting



and dwelling conditions of households. Furthermore, the survey includes information about ownership, use, and vintage of three types of appliances: AC, REF, and TV. In this survey, the types of lamps installed in the room (incandescent, fluorescent, LED) are reported.

4.2 Air conditioner

In the survey, 10,191 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 degrees in the survey sheet. Figure 2 shows that the distribution of the set temperate is left-skewed. Although the most popular set temperature is 28 degrees Celsius, the average temperature is 26.79 degrees Celsius.

In the survey, the vintage of ACs is classified into six periods. Households were asked to choose the vintage of their main AC from these six periods. The division of vintage period and the share of ACs manufactured in each vintage period are as follows: before 1990 (3.65%), 1991-1995 (4.20%), 1996-2000 (10.29%), 2001-2005 (18.44%), 2006-2010 (30.42%), and after 2011 (33.00%).

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

4.3 Lamp

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 according to the situation. This adjustment includes the light reduction as well as the use of automatic light control function. In total, 9677 households responded to this question properly. While 66.2% of households answered that they were adjusting the brightness, the remaining 33.8% said that they were not. In the second question, households were asked whether they switch off lights when leaving a room even for a short time. For this question, 11,590 households responded to this question properly. While 81.9% of households answered that they were switching off the light, the remaining 18.1% said that they were not.

In the survey, households were asked the type of lamps used in five types of rooms: living, kitchen, dining, bed, and other rooms. According to the installation condition of the lamps, we classified households into three types. The first type of households is zero LEDization households who did not install LED in any room. The second type of household is complete LEDization household who were using only LEDs in all rooms. LEDs are energy efficient and last longer than conventional incandescent lighting. According to the U.S. Department of Energy (2015), residential LEDs use at least 75% less energy and last 25 times longer than incandescent lighting. In the following analysis, we investigate whether the brightness adjustment and switch-off practice differ depending on the differences in LEDization stage.

4.4 Refrigerator

There are two questions related to refrigerator use. In the first question, households were asked whether they were adjusting the temperature setting of the refrigerator according to the season. In the survey, 6,144 households out of 11,598 households who replied the question properly, answered they were adjusting the temperature setting. Therefore, about 53.2% of households were adjusting the temperature and about 46.8% were not. In the second question, household were asked whether they avoid overstuffing causing cooling efficiency loss. To this second question, 7,793 households out of 11,598 households who replied the question properly, answered they avoided overstuffing. Therefore, about 67.6% of households avoided overstuffing and about 32.4% did not.

The classification of REF vintage is the same as the one of AC. The share of REFs manufactured in each vintage period are as follows: before 1990 (2.73%), 1991-1995 (3.79%), 1996-2000 (11.55%), 2001-2005 (19.88%), 2006-2010 (32.82%), and after 2011 (29.23%). In the following analysis, we examine whether the vintage of REFs affect temperature setting or overstuffing.

4.5 Television

In SCDEH, two types of curtailment actions related to TV use were surveyed. In the first question, households were asked whether they adjust the brightness of their TV. In total, 10,712 households replied to this question properly and 38.4% of them answered that they were adjusting the brightness. In the second question, households were asked whether they turn off the main switch of TVs when not used. Once again, 10,712 households replied to this question properly and 37.2% of them answered that they switched off TVs.

The vintage of their main TV was surveyed. The share of REFs manufactured in each vintage period are as follows: before 1990 (0.59%), 1991-1995 (1.05%), 1996-2000 (3.35%), 2001-2005 (9.84%), 2006-2010 (52.83%), and after 2011 (32.35%). In the following analysis, we examine whether households using a new or old TV engage in the above mentioned energy saving practices related to TV use.

People watching televisions for long time may not turn off the main switch. Since the time spent watching TV may be correlated to energy saving practice, we include the time spending for TV watch in the following analysis.

4.6 Other covariates

We include household income, age of household head, child dummy, senior dummy, and job dummy. We also include the variables related to housing conditions: detached house dummy, floor area, and ownership dummy. The definition and descriptive statistics of socioeconomic and housing condition variables are presented in Table 2.

Table 2. Descriptive statistics of explanatory variables (N = 8,636)

Variable	Definition and unit	Mean or share	Std. Dev.
Price of electricity	yen/kWh	26.59	4.32
Household income[1]	10,000 yen	571.04	348.18
Age of household head[2]	years old	56.86	13.94
Children	dummy: 1 = there are children below 10, 0 = if not	0.17	
Teen	dummy: 1 = there are teens between 10 and 19	0.21	
Senior	dummy: 1 = there are persons above 75	0.40	
Job	dummy: 1 = there are children below 12	0.70	
Propensity of wasting electricity	score: 1 - 5	1.29	1.06
Ownership of house	dummy: 1 = own house, 0 = else	0.81	
Detached house	dummy: 1 = detached house, 0 = else	0.72	
Floor area	m^2	115.37	58.77

Note. 1. Household income is classified into 7 groups and we use the median income of each group: Group 1 = 125, Group 2 = 375, Group 3 = 625, Group 4 = 875, Group 5 = 1250, Group 6 and 7 = 1750.
2. A person is classified into 7 age groups and we use the median income of each group: Group 1 = 25, Group 2 = 35, Group 3 = 45, Group 4 = 55, Group 5 = 62, Group 6 = 70, Group 7 = 80.

In SCDEH, households were asked for electricity consumption and electricity bill. We divide electricity bill by electricity consumption to calculate the electricity price and include the electricity price calculated in the following analysis, to assess whether energy saving practices are promoted by higher electricity price.

In addition to the curtailment actions of TV, REF, LAMP, and AC use, households were asked the practice of other five type of curtailment actions.

Table 3. Determinants of curtail actions

	AC (N = 6786)		TV (N= 6945)				REF (N = 6967)			
	set temperature		brightness adjust.		switch off		temperature adjust.		avoid overstuffing	
	Coeff.	Std. Err.	Coeff.	Std. Err.	Coeff.	Std. Err.	Coeff.	Std. Err.	Coeff.	Std. Err.
Price of electricity	-0.01*** A	0.00	-0.01	0.01	-0.002	0.01	-0.01	0.01	0.00	0.01
Household income	-5.7E-05B	5.8E-05	-7.70E-5	8.4E-05	-1.5E-04	0.00	-2.2E-04**	8.2E-05	-3.3E-04***	8.6E-05
Age of household head	-1.7E-05	2.2E-03	-0.01**	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Children	0.07	0.05	-0.10	0.08	0.03	0.08	0.06	0.07	-0.10	0.08
Teen	-0.13***	0.04	0.14**	0.07	0.08	0.07	0.05	0.07	-0.12*	0.07
Senior	-0.12**	0.05	-0.05	0.08	-0.08	0.08	0.08	0.08	-0.07	0.08
Job	-0.23***	0.05	0.09	0.08	-0.01	0.08	0.13	0.08	0.01	0.08
Propensity of wasting electricity	-0.10***	0.02	-0.26***	0.03	-0.43***	0.03	-0.40***	0.03	-0.34***	0.03
Ownership of house	0.26***	0.06	0.02	0.09	0.06	0.09	0.07	0.09	0.04	0.10
Detached house	-0.06	0.06	-0.13	0.08	0.05	0.08	-0.07	0.08	-0.16	0.09
Floor area	-0.001	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Vintage	-0.01**	0.00	-0.004	0.004	0.02***	0.00	-0.02***	0.00	-0.02***	0.00
Usage	-0.01***	0.00	-0.05**	0.02	-0.15***	0.02				
Number	-0.01	0.01								
Size							1.7E-04	2.2E-04	2.3E-04	2.3E-04
Constant	27.88***	0.21	0.83**	0.31	0.24	0.32	0.82**	0.31	1.69***	0.33
LR Chi 2	482.62 (df = 60)		314.29 (df = 59)		436.82 (df = 59)		397.80 (df = 59)		348.91 (df = 59)	

Note. A. *, **, and *** indicate statistically significant at 10 percent, 5 percent, and 1 percent levels, respectively.
B. -5.7E-05 is -0.000057.

According to the response to these actions, we measure the propensity of wasting electricity of each household. We expect that a household wasting electricity for one appliance will waste electricity for other appliances also.

5 Empirical models and results

As for curtailment actions of LAMP, REF, and TV, households were asked if they are practicing those actions or not. Thus, we use logistic model for the following analysis. In contrast, we use a double censored Tobit model for the analysis of AC since households were asked to choose their set temperature between 17 and 32 degrees Celsius. The number of households that properly answered the question on curtailment actions is different and therefore the number of samples varies between models.

Table 3 presents the results of AC, TV, and REF. In all models, we obtained the negative sign for the variable of the propensity of wasting electricity. It means that the person not taking an energy conservation practice for one appliance will not take an energy saving practice for other appliances.

The set temperature becomes low if head of household is working outside, if teenagers or seniors are at home, if households live in a large house of their own, and if AC is used for long hours. We also found that a households using an old AC tends to set AC temperature low. This may simply mean that households needed to set the temperature low since the cooling performance of their old ACs declined. Yet, at least, we do not find the evidence in which households start

Table 4. Determinants of curtail actions

	LAMP (N = 6945)			
	brightness adjust.		switch off	
	Coeff.	Std. Err.	Coeff.	Std. Err.
Price of electricity	0.02**A	0.01	2.93E-3	9.04E-3
Household income	1.4E-04B	1.1E-04	1.4E-04	1.1E-04
Age of household head	0.008**	0.003	0.00	0.00
Children	0.24***	0.08	0.20**	0.10
Teen	-0.01	0.07	0.08	0.08
Senior	0.03	0.08	0.08	0.10
Job	0.05	0.08	-0.08	0.10
Propensity of wasting electricity	-0.41***	0.03	-0.44***	0.03
Ownership of house	-0.05	0.09	0.13	0.12
Detached house	0.17**	0.08	0.03	0.10
Floor area	-8.0E-05	5.7E-04	5.7E-04	7.2E-04
Zero Ledization	-0.63***	0.05	0.02	0.07
Complete Ledization	0.08	0.11	-0.01	0.13
Constant	0.95***	0.31	2.08***	0.38
LR Chi 2	548.89 (df = 59)		436.82 (df = 59)	

Note. A. *, **, and *** indicate statistically significant at 10 percent, 5 percent, and 1 percent levels, respectively.
B. 1.4E-04 is 0.00014.

paying less attention to energy consumption and reducing the set temperature, after purchasing an efficient AC.

The age of household head is negatively associated with the brightness adjustment of TV while the presence of teenagers is positively associated with it. People watching TV for long hours do not adjust the brightness of the TV. Although we only focus on the households using liquid crystal TV in this study, we do not find any meaningful relationship between TV vintage and brightness adjustment. Households watching TV for long hours replied that they do not turn off the main switch of TV even when not used. In contrast, households using an old TV replied that they turn off the main switch of TV comparing to those using a new TV.

About REF use, we find that wealthy households do not adjust the temperature of their refrigerator. In addition, they don't concern overstuffing. Households using refrigerators answered that they adjust the temperature according to season and intend to avoid overstuffing. Remaining socioeconomic and housing variables are not correlated with the curtailment actions of REF.

Table 4 presents the estimation results of the curtailment actions related to lighting. Brightness adjustment is carried out if the age of household head is high or if there are children at home. In addition, the result shows that the brightness adjustment is more common in detached houses. With respect to the LEDization, we found that households not installing LEDs into any room answered that they did not adjust the brightness. It suggests that curtailment action can be also enhanced through LED promotion. Although child presence is positively associated with the switch off activity, other socioeconomic and housing variables are not associated with it.

6 Conclusion and policy implication

For energy saving, a household invests energy efficiency but takes curtailment action simultaneously. 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 the two measures. In this study, we developed an energy-saving model based on the household production framework and analyzed how a household uses two energy-saving measures. If energy-saving products become available at lower cost, we expect that a household will increase efficiency investment and will reduce curtailment action. However, we show that a household do not necessarily reduce curtailment action when a time allocation problem between energy-saving and other entertainment activities is considered. If the price of energy-efficient products decreased, energy service becomes available at lower cost. Hence, energy service becomes more attractive than 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 becomes important to know how households' curtailment action is associated with efficiency investment decision. Our empirical analysis reveals that a household using new appliances rather takes high-level curtailment actions. The result predicts that curtailment action will not be discouraged by the promotion of energy-efficient products. Although governments often introduce policies to promote energy-efficient products, our results suggests that such government promption policies will not crowd out households' curtailment action.

Our empirical analysis showed that personality type influences energy-saving actions greatly. Those who do not invest in energy saving do not practice energy saving. Those who continue to use old appliances do not know the energy efficiency and do not take curtailment action. In short, they pay less attention to electricity consumption. Policies that make people having less sense of energy saving invest in energy efficiency would be necessary. One of such policies is scrap incentive program in which a household is benefited when replacing an old appliance with a new one. Alternatively, governments can differentiate a recycling fee according to the vintage of the appliances.

Acknowledgements

The first author receives financial support from the Environment Research and Technology Development Fund (2-1707) of the Environmental Restoration and Conservation Agency as well as KAKENHI (18K01578) of the Japan Society for the Promotion of Science.

Appendix 1: Derivation of the unit cost of entertainment activity p_Z

The cost minimization problem for the entetainment activity is defined by

$$\mathcal{L}_Z \equiv P_X X + P_L L + P_Z \left(Z - X^{\delta} L^{1-\delta} \right).$$

The first-order conditions are

$$\begin{aligned} \frac{\partial \mathcal{L}_Z}{\partial X} &= P_X - P_Z \delta X^{\delta-1} L^{1-\delta} = 0, \\ \frac{\partial \mathcal{L}_Z}{\partial L} &= P_L - P_Z (1-\delta) X^{\delta} L^{-\delta} = 0. \end{aligned}$$

These two conditions can be written as

$$P_X = \frac{\delta P_Z Z}{X}, \qquad P_L = \frac{(1-\delta) P_Z Z}{L}.$$

By combining the above two conditions, we obtain

$$L = \left(\frac{P_L}{1-\delta} \right)^{-1} \left(\frac{P_X}{\delta} \right) X.$$

Substituting this into $Z = X^{\delta} L^{1-\delta}$ yields

$$Z = \left(\frac{P_L}{1-\delta} \right)^{-(1-\delta)} \left(\frac{P_X}{\delta} \right)^{1-\delta} X.$$

Solving this for X yields the conditional demand for X:

$$X = \left(\frac{P_X}{\delta} \right)^{-1} \left(\frac{P_L}{1-\delta} \right)^{1-\delta} \left(\frac{P_X}{\delta} \right)^{\delta} Z.$$

The conditional demand for L is

$$L = \left(\frac{P_L}{1-\delta} \right)^{-1} \left(\frac{P_L}{1-\delta} \right)^{1-\delta} \left(\frac{P_X}{\delta} \right)^{\delta} Z.$$

Hence the unit cost of generating Z is

$$P_Z = \frac{P_X X + P_L L}{Z} = \left(\frac{P_L}{1-\delta} \right)^{1-\delta} \left(\frac{P_X}{\delta} \right)^{\delta}.$$

Appendix 2: Derivation of the unit cost of energy saving activity P_H

The cost minimization problem for the energy saving activity is defined by

$$\mathcal{L}_H \equiv P_K K + P_C C + P_H \left\{ H - \left(\eta K^{\rho} + (1-\eta) C^{\rho} \right)^{\frac{1}{\rho}} \right\}.$$

The first-order conditions are

$$\begin{aligned} \frac{\partial \mathcal{L}_H}{\partial K} &= P_K - P_H \left(\eta K^{\rho} + (1-\eta) C^{\rho} \right)^{\frac{1}{\rho}-1} \eta K^{\rho-1} = 0, \\ \frac{\partial \mathcal{L}_H}{\partial C} &= P_C - P_H \left(\eta K^{\rho} + (1-\eta) C^{\rho} \right)^{\frac{1}{\rho}-1} (1-\eta) C^{\rho-1} = 0. \end{aligned}$$

These two conditions can be written as

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

By combining the above two conditions, we obtain

$$K = \left(\frac{P_K}{\eta}\right)^{\frac{1}{\rho-1}} \left(\frac{P_C}{1-\eta}\right)^{-\frac{1}{\rho-1}} C$$

Substituting this into $H^{\rho} = \eta K^{\rho} + (1-\eta) C^{\rho}$ yields

$$H = \left\{\eta \left(\frac{P_K}{\eta}\right)^{\frac{\rho}{\rho-1}} + (1-\eta) \left(\frac{P_C}{1-\eta}\right)^{\frac{\rho}{\rho-1}}\right\}^{\frac{1}{\rho}} \left(\frac{P_C}{1-\eta}\right)^{-\frac{1}{\rho-1}} C.$$

Solving this for C yields the conditional demand for C:

$$C = \left(\frac{P_C}{1-\eta}\right)^{\frac{1}{\rho-1}} \left\{\eta \left(\frac{P_K}{\eta}\right)^{\frac{\rho}{\rho-1}} + (1-\eta) \left(\frac{P_C}{1-\eta}\right)^{\frac{\rho}{\rho-1}}\right\}^{-\frac{1}{\rho}} H$$

The conditional demand for K is

$$K = \left(\frac{P_K}{\eta}\right)^{\frac{1}{\rho-1}} \left\{\eta \left(\frac{P_K}{\eta}\right)^{\frac{\rho}{\rho-1}} + (1-\eta) \left(\frac{P_C}{1-\eta}\right)^{\frac{\rho}{\rho-1}}\right\}^{-\frac{1}{\rho}} H.$$

Hence the unit cost of producing H is

$$P_H = \frac{P_K K + P_C C}{H} = \left[\eta \left(\frac{P_K}{\eta}\right)^{\frac{\rho}{\rho-1}} + (1-\eta) \left(\frac{P_C}{1-\eta}\right)^{\frac{\rho}{\rho-1}}\right]^{\frac{\rho-1}{\rho}}.$$

Appendix 3: Derivation of Marshallian demands entertainment activity Z and energy energy service S

The Lagrangian for this problem is

$$\mathcal{L} \equiv \left(\beta Z^{\alpha} + (1-\beta) S^{\alpha}\right)^{\frac{1}{\alpha}} + \lambda \left(Y - P_Z Z - P_S S\right).$$

with the associated first-order conditions:

$$\begin{aligned}
\frac{\partial \mathcal{L}}{\partial Z} &= \frac{1}{\alpha} \left(\beta Z^{\alpha} + (1-\beta) S^{\alpha}\right)^{\frac{1}{\alpha}-1} \beta \alpha Z^{\alpha-1} - \lambda P_Z = 0, \\
\frac{\partial \mathcal{L}}{\partial S} &= \frac{1}{\alpha} \left(\beta X^{\alpha} + (1-\beta) S^{\alpha}\right)^{\frac{1}{\alpha}} (1-\beta) \alpha S^{\alpha-1} - \lambda P_S = 0.
\end{aligned}$$

Using the first-order conditions, we obtain

$$Z = \left(\frac{P_Z}{\beta}\right)^{-\frac{1}{1-\alpha}} \left(\frac{P_S}{1-\beta}\right)^{\frac{1}{1-\alpha}} S.$$

Substituting this into the full income constraint ($P_Z Z + P_S S = Y$), we obtain

$$\begin{aligned} S &= \left(\frac{P_S}{1-\beta}\right)^{-\frac{1}{1-\alpha}} \left\{\beta\left(\frac{P_Z}{\beta}\right)^{\frac{\alpha}{\alpha-1}} + (1-\beta)\left(\frac{P_S}{1-\beta}\right)^{\frac{\alpha}{\alpha-1}}\right\}^{-1} Y \\ &= \left(\frac{P_S}{1-\beta}\right)^{-\frac{1}{1-\alpha}} P^{\frac{\alpha}{1-\alpha}} Y. \end{aligned}$$

From $Z = \left(\frac{P_Z}{\beta}\right)^{-\frac{1}{1-\alpha}} \left(\frac{P_S}{1-\beta}\right)^{\frac{1}{1-\alpha}} S$, we get

$$\begin{aligned} Z &= \left(\frac{P_Z}{\beta}\right)^{\frac{1}{\alpha-1}} \left\{\beta\left(\frac{P_Z}{\beta}\right)^{\frac{\alpha}{\alpha-1}} + (1-\beta)\left(\frac{P_S}{1-\beta}\right)^{\frac{\alpha}{\alpha-1}}\right\}^{-1} Y \\ &= \left(\frac{P_Z}{\beta}\right)^{-\frac{1}{1-\alpha}} P^{\frac{\alpha}{1-\alpha}} Y. \end{aligned}$$

By substituting S and Z into utility function, we have

$$U = Y \left\{\beta\left(\frac{P_Z}{\beta}\right)^{\frac{\alpha}{\alpha-1}} + (1-\beta)\left(\frac{P_S}{1-\beta}\right)^{\frac{\alpha}{\alpha-1}}\right\}^{-\frac{\alpha-1}{\alpha}}.$$

Therefore, we can show

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

Appendix 4: Derivation of the derived demands for energy use E, energy saving activity H, efficiency investment K and curtailment action C

To obtain the derived demand for E, we first apply Shepherd's lemma to the cost function $P_S S$:

$$E = \frac{\partial P_S}{\partial P_E} S = \frac{1-\gamma}{P_E} P_S S$$

Substituting for $S = \left(\frac{P_S}{1-\beta}\right)^{\frac{1}{\alpha-1}} P^{-\frac{\alpha}{\alpha-1}} Y$ yields

$$E = \frac{\delta(1-\gamma)(1-\beta)}{P_E} \left(\frac{P_S}{1-\beta}\right)^{\frac{\alpha}{\alpha-1}} P^{-\frac{\alpha}{\alpha-1}} Y.$$

Similarly, we find the derived demand for H by applying Shepherd's lemma to the cost function $P_S S$:

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

We next find the derived demand for K and C. Substituting $H = \frac{\delta\gamma(1-\beta)}{P_H}\left(\frac{P_S}{1-\beta}\right)^{\frac{\alpha}{\alpha-1}} P^{-\frac{\alpha}{\alpha-1}}Y$ the conditional demands for K gives

$$\begin{aligned} K &= \left(\frac{P_K}{\eta}\right)^{\frac{1}{\rho-1}} P_H^{-\frac{1}{\rho-1}} H \\ &= \delta\gamma(1-\beta)\left(\frac{P_K}{\eta}\right)^{\frac{1}{\rho-1}} \left(\frac{P_S}{1-\beta}\right)^{\frac{\alpha}{\alpha-1}} P_H^{\frac{\rho}{1-\rho}} P^{-\frac{\alpha}{\alpha-1}} Y. \end{aligned}$$

Similarly, from $H = \frac{\delta\gamma(1-\beta)}{P_H}\left(\frac{P_S}{1-\beta}\right)^{\frac{\alpha}{\alpha-1}} P^{-\frac{\alpha}{\alpha-1}}Y$, we get

$$\begin{aligned} C &= \left(\frac{P_C}{1-\eta}\right)^{\frac{1}{\rho-1}} P_H^{-\frac{1}{\rho-1}} H \\ &= \delta\gamma(1-\beta)\left(\frac{P_C}{1-\eta}\right)^{\frac{1}{\rho-1}} \left(\frac{P_S}{1-\beta}\right)^{\frac{\alpha}{\alpha-1}} P_H^{\frac{\rho}{1-\rho}} P^{-\frac{\alpha}{\alpha-1}} Y. \end{aligned}$$

References

Agency of Natural Resources and Energy of Japan. 2019. About Top Runner Program. <https://www.enecho.meti.go.jp/category/saving_and_new/saving/enterprise/about-reguration/benchmark/> Accessed 4 May 2019.

Allcott, H. 2011. Social norms and energy conservation. Journal of Public Economics, 95 (9–10): 1082–1095. doi:10.1016/j.jpubeco.2011.03.003.

Allcott, H. and Mullainathan, S. 2010. Behavioral and energy policy. Science, 327: 1204–1205. doi:10.1126/science.1180775

Belaid, F. and Garcia, T. 2016. Understanding the spectrum of residential energy-saving behaviours: French evidence using disaggregated data. Energy Economics 57: 204–214. doi:10.1016/j.eneco.2016.05.006.

Brechling, V. and Smith S. 1994. Household energy efficiency in the UK. Fiscal Studies 15: 44–56. doi:10.1111/j.1475-5890.1994.tb00196.x.

Brounen, D., Kok, N., and Quigley, J. 2013. Energy literacy, awareness, and conservation behavior of residential households. Energy Economics 38: 42–50. doi:10.1016/j.eneco.2013.02.008.

Botetzagias, I., Malesios, C., and Poulou, D. 2014. Electricity curtailment behaviors in Greek households: Different behaviors, different predictors. Energy Policy 69: 415–424. doi:10.1016/j.enpol.2014.03.005.

European Commission. 2019. Energy Efficiency: Saving energy, saving money. <https://ec.europa.eu/energy/en/topics/energy-efficiency> Accessed 4 May 2019.

Frederiks, E., Stenner, K., and Hobman, E. 2015. Household energy use: Applying behavioural economics to understand consumer decision-making and behavior. Renewable and Sustainable Energy Reviews, 4: 1385–1394. doi: 10.1016/j.rser.2014.09.026.

Gronau, R. and Hamermesh, D. 2006. Time vs. goods: the value of measuring household technologies. Review of Income and Wealth 52: 1–16. doi: 10.1111/j.1475-4991.2006.00173.x.

Gronau, R. and Hamermesh, D. 2008. The Demand for Variety: A Household Production Perspective. The Review of Economics and Statistics, 90 (3): 562–572. doi: 10.1162/rest.90.3.562.

Hori, S., Kondo, K., Nogata, D., and Ben,. 2013. The determinants of household energy-saving behavior: Survey and comparison in five major asian cities. Energy Policy 52: 354–362. doi:10.1016/j.enpol.2012.09.043.

Karlin, B., Davis, N., Sanguinetti, A., Gamble, K., Kirkby, D., and Stokols, D. 2014. Dimensions of conservation: exploring differences among energy behaviors. Environmental Behavior, 46(4): 423–452. doi:10.1177/0013916512467532.

Lange, I., Moro, M., and Traynor, L. 2014. Green hypocrisy?: Environmental attitudes and residential space heating expenditure. Ecological Economics, 107: 76–83. doi:10.1016/j.ecolecon.2014.07.021

Levinson, A. and Niemann, S. 2004. Energy use by apartment tenants when landlords pay for utilities. Resource and Energy Economics, 26: 51–75.

Lillemo, S.C. 2014. Measuring the effect of procrastination and environmental awareness on households' energy-saving behaviours: An empirical approach. Energy Policy 66: 249–256. doi: 10.1016/j.enpol.2013.10.077.

Mills, B. and Schleich, J. 2012. Residential energy-efficient technology adoption, energy conservation, knowledge, and attitudes: An analysis of european countries. Energy Policy 49: 616–628. doi:10.1016/j.enpol.2012.07.008.

Ministry of the Environment of Japan. 2016. Survey on the carbon dioxide emissions from households.

Nakamura, H. 2013. Effects of social participation and the emergence of voluntary social interactions on household power-saving practices in post-disaster Kanagawa, Japan. Energy Policy 54: 397–403. doi:10.1016/j.enpol.2012.11.041.

Ramos, A., Labandeira, X., and Loschel, A. 2016. Pro-environmental households and energy efficiency in Spain. Environmental and Resource Economics 63: 367–393. doi:10.1007/s10640-015-9899-8.

Rapson D. 2014. Durable goods and long-run electricity demand: evidence from air conditioner purchase behavior. Journal of Environmental Economics and Management 68:141–160. doi:10.1016/j.jeem.2014.04.003.

Tiefenbeck, V., Staake, T., Roth, K., and Sachs, O. 2013. For better or for worse? Empirical evidence of moral licensing in a behavioral energy conservation campaign. Energy Policy, 57: 160–171. doi:10.1016/j.enpol.2013.01.021.

Traynor, L., Lange, I., and Moro, M. 2014. Green hypocrisy?: Environmental attitudes and residential space heating expenditure. Ecological Economics, 107: 76–83. doi:10.1016/j.ecolecon.2014.07.021.

Trotta, G. 2018. Factors affecting energy-saving behaviours and energy efficiency investments in british households. Energy Policy 114: 529–539. doi: 10.1016/j.enpol.2017.12.042.

Tsvetanov, T. and Kathleen Segerson, K. 2014. The Welfare Effects of Energy Efficiency Standards When Choice Sets Matter. Journal of the Association of Environemntal and Resource Economists 1: 233–271. doi:10.1086/676036.

Urban, J. and Ščasny, M. 2012. Exploring domestic energy-saving: the role of environmental concern and background variables. Energy Policy, 47: 69–80. doi: 10.1016/j.enpol.2012.04.018.

U.S. Department of Energy. 2015. LED lighting. <https://energy.gov/energysaver/save-electricity-and-fuel/lighting-choices-save-you-money /led-lighting> (accessed on 17 February 2018)

U.S. Department of Energy. 2019. Energy Efficiency Policies and Programs. <https://www.energy.gov/eere/slsc/energy-efficiency-policies-and-programs> Accessed 4 May 2019.

Wang, Z., Zhang, B., Yin, J., and Zhang, Y. 2011. Determinants and policy implications for household electricity-saving behaviour: Evidence from Beijing, China. Energy Policy 39: 3550–3557. doi:10.1016/j.enpol.2011.03.055.