Research Institute for Environmental Economics and Management

Discussion Paper Series No.1803

How much household electricity consumption is actually saved by replacement with Light-Emitting Diodes (LEDs)?

Hiroki Onuma, Shigeru Matsumoto, & Toshi H. Arimura

August 2018

WASEDA

How much household electricity consumption is actually saved by replacement with Light-Emitting Diodes (LEDs)?

Hiroki Onuma[1,4], Shigeru Matsumoto[2,4], Toshi H. Arimura[3,4]

Abstract

Many countries have promoted the replacement of conventional lamps with next-generation lamps to reduce electricity usage for lighting. In Japan, the majority of the lamps sold at home appliance mass merchant shops have been changed from incandescent lamps to energy-saving lamps. All conventional lamps are planned to be replaced with light-emitting diodes (LEDs) by 2020. Although the energy saving effect of LEDs has been stressed in many engineering studies, studies have not examined how much electricity has actually been saved by the installation of LEDs. Using micro-level data from the Survey on Carbon Dioxide Emission from Households (SCDEH), we compare monthly electricity usage between households using conventional lamps and those using LEDs. Our empirical result demonstrates that the installation of LEDs can reduce household electricity usage by 2.3%-2.8%. However, this saving rate is smaller than that expected from the engineering calculation. This result suggests the possibility of a rebound effect associated with LED installation. The empirical result further demonstrates that middle-income households have higher price elasticity of electricity demand and are more likely to receive greater benefit from LED installation.

JEL classification: C23, D12, Q41
Keywords: Electricity Usage, Energy Saving, LED, Household-Level Data, Conditional Demand Analysis

---

[1] Organization for University Research Initiatives, Waseda University
Address: #965, Bldg. 9, 1-6-1 Nishiwaseda, Shinjuku-ku, Tokyo 169-8050, Japan.
Email: h.onuma.ac@gmail.com

[2] Faculty of Economics, Aoyama Gakuin University
Email: shmatsumoto@aoyamagakuin.jp

[3] Faculty of Political Science and Economics, Waseda University
Email: toshi.arimura@gmail.com

[4] Research Institute for Environmental Economics and Management, Waseda University

1. Introduction

According to an estimation by International Energy Agency (2016), the residential sector accounted for 21% of the final energy consumption worldwide in 2013. Although there are considerable variations in energy usage across countries, on average, households use 52% of energy for space heating. Compared to the share for space heating, the share of energy consumption for lighting is relatively small and accounts only for 4%.

Therefore, the importance of lighting in energy consumption is relatively small. Nevertheless, countries have undertaken great efforts to reduce electricity usage for lighting. Many countries have introduced a phase-out program of incandescent lamps, and some countries have banned their sales (Dick 2016). The European Commission adopted a regulation on non-directional household lamps that aimed to replace inefficient incandescent lamps with more efficient alternatives in March 2008 (European Commission 2009). The ban was enforced against almost all types of incandescent lamps in 2017.[1] The US President George W. Bush signed into law the Energy Independence and Security Act of 2007 in December 2007. Although this act does not directly prohibit the sales of incandescent lamps, it requests an increase in the energy efficiency of lamps by 25% from 2012 to 2014 (US Department of Energy 2012; US Environmental Protection Agency 2011). Consequently, the act "effectively" bans the manufacturing and importing of conventional incandescent lamps.

The Japanese government asked domestic manufacturers to stop the production of incandescent lamps in 2008. Since then, the majority of the lamps sold at home appliance mass merchant shops have been changed from incandescent lamps to energy-saving lamps. In November 2015, the Japanese government announced the idea of strengthening the regulation

[1] Currently, non-directional halogen lamps, such as standard GLS or candle lamps, are treated as exceptions. However, they will also be banned in September 2018 (Lightbulbs Direct 2018).

of incandescent and fluorescent lamps and accelerated their replacement with light-emitting diodes (LEDs) to improve the energy efficiency of houses (Nippon Television 2015). In Japan, both incandescent and fluorescent lamps are planned to be replaced with LEDs by 2020.

LEDs are energy efficient and last longer than conventional incandescent lighting. According to the US Department of Energy (2015), residential LEDs use at least 75% less energy and last 25 times longer than incandescent lighting. Therefore, households can reduce their electricity bills by installing LEDs. Despite this cost advantage, LEDs have not been popular technology until recently. Some consumers have complained that LEDs emit a cold, unnatural light compared to conventional lamps. Other consumers complain about the cost of LEDs. Previous studies have repeatedly reported that high upfront costs of energy-efficient products discourage consumers from purchasing them (Poortinga et al. 2003; Gillingham, Newell, & Palmer 2009; Nair, Gustavsson, & Mahapatra 2010; Karlin et al. 2014; Frederiks, Stenner, & Hobman 2015; Matsumoto 2015). In recent years, scholars have investigated household investment in energy saving lamps (Mills and& Schleich 2010; Gram-Hanssen 2013; Ameli & Brandt 2015). These studies confirmed that household income determines the investment decision regarding energy-efficient lamps; in particular, they found that high upfront cost discourages low-income households from purchasing energy-efficient lamps.

Thomas Edison's great invention (the incandescent lamp) has changed our daily life drastically. His invention enabled us to perform tasks at night time that used to be possible only during the day. Will LEDs also change our daily life by lighting homes at a much lower cost?

The replacement of incandescent lights with LEDs is expected to accelerate increasingly in the near future. Though engineers provide estimates of cost saving in an ideal situation, studies have not yet investigated how the electricity usage of households is changed *in reality* by replacement with LEDs. The cost savings from LED installation depends on how consumers behave after they install LEDs. For example, if consumers understand the efficiency of LEDs, they may leave their LED lights on more than before. In this case, the cost savings from LED may not be as large as engineers predict.[2] Is there a difference in the size of the benefits of energy savings across households? Who will receive the greatest benefit from LED installation? We answer these questions in this paper.

The efficiency improvement of an energy-consuming durable lowers the effective price of the service it provides and consequently increases demand for that service (Jevons 1865). The so-called "Jevons Paradox" has been studied extensively, mostly in terms of the "rebound effect." Although the size of the rebound effect is estimated to be relatively small, the presence of the rebound effect has been confirmed in many studies (Greening, Greene, & Difiglio 2000; Nadel 2012). In addition, it has been confirmed that efficiency improvement creates financial savings and increases demand for the services of other energy-consuming durable goods. Several studies report that such indirect rebounds can be sizeable (Chitnis et al. 2013; Chitnis & Sorrell 2015; Inoue & Matsumoto 2017). To estimate the size of the rebound effect of LED installation, we compare the electricity saving estimated from survey data with the amount calculated by the engineering study.

The rest of the paper is organized as follows. In the next section, we provide background information about the Japanese lighting market. We also summarize the electricity usage of Japanese households. In this study, we use micro-level data from the Survey on Carbon Dioxide Emission from Households (SCDEH) (Ministry of the Environment of Japan 2016). We provide information about the SCDEH and summarize the data in Section 3. After controlling

[2] There is an opinion that the banning of incandescent lamps has not achieved as much of a reduction in energy use as was initially hoped. Households increased the number of lamps in the home and switched to halogen downlighters (Hickman 2012).

for dwelling characteristics, socioeconomic characteristics, appliance ownership, and geographical conditions of households, we compare monthly electricity usages between households using conventional lamps and those using LEDs. Section 4 presents the estimation model, and Section 5 reports the empirical findings. The empirical result demonstrates that households can reduce their household electricity usage by 2.3%-2.8% with the installation of LEDs. The empirical result further shows that middle-income households have higher price elasticity and are likely to receive greater benefit from LED installation. Section 6 makes policy recommendations based on the empirical findings.

2. Japanese Lighting Market

According to the statistics from the Agency for Natural Resources and Energy of Japan (2015), the final energy consumptions of the industry, commercial, household, and transportation sectors were 6.14, 2.46, 1.87, and 3.08 $\times 10^{18}$J, respectively. Thus, the household sector accounted for 13.8% of the final energy consumption in 2015. In terms of the composition of energy sources, electricity, city gas, LP gas, kerosene, and solar constituted 16,918, 7,062, 3,519, 5,135, and 260 $\times 10^6$J, respectively (Institute of Energy Economics of Japan 2015). Therefore, the share of electricity was approximately 52.5% in 2015.

Figure 1 presents the historical change in the monthly electricity usage of the average Japanese household. The electricity usage showed an upward trend until 2010. However, it became a downward trend after the Great East Japan Earthquake in 2011. In 2015, the average Japanese household used approximately 247.8 kWh of electricity per month. Based on an estimation by the Institute of Energy Economics of Japan (2015), the average household uses 708$\times 10^6$J of electricity for space cooling, 7,367$\times 10^6$J for space heating, 9,495$\times 10^6$J for water heating, 3,069$\times 10^6$J for cooking, and 12,256 $\times 10^6$J for lighting and appliances. According to the estimation by the Ministry of Economy, Trade, and Industry (METI) of Japan (2011), the average household allocated approximately 13.4% of electricity for lighting in 2009.

In June 2010, the Cabinet approved the New Growth Strategy and established the installation of next-generation lighting systems as one of the national strategies for creating an environmentally friendly and energy efficient country through green innovations. According to the target, 100% of LED and organic EL lighting will be realized by 2020 on a flow basis and by 2030 on a stock basis. To accelerate the lighting renovation of factories and business offices, many local governments have introduced various subsidy programs. Due to a series of such promotion policies, LEDs have become popular in Japan.

The Japan Lighting Manufacturers Association (JLMA) conducts a survey on shipping status among its member companies every year. Figure 2 presents the historical change in the share of the shipment of lamps from the JLMA (2018). The figure clearly shows that the market share of LEDs has been expanding while the shares of incandescent lamps (general and micro lamps) and fluorescent lamps have been decreasing. Nevertheless, the market share of LEDs increased from 2.0% in 2010 to 14.4% in 2017 alone. This is not a sufficient pace to achieve the LED replacement target by 2020.

3. Data

3.1. Data Source

The data used in this analysis are obtained from the SCDEH (MOEJ, 2016)[3]. The SCDEH is a monthly survey conducted by the Ministry of the Environment of Japan (MOEJ) between

[3] This survey was a pilot survey. The actual survey (the Statistical Survey on Actual Carbon Dioxide Emission from Households) began in April 2017.

October 2014 and September 2015. It uses both in-person and Internet surveys and includes samples of 16,402 households (8,802 households from the in-person survey and 7,600 households from the Internet survey) from all parts of Japan. As the title of the survey suggests, the survey is designed to study the energy usage of households. Information about the monthly electricity usage of individual households is also included. The survey contains household information typically included in the analysis of household electricity usage (Frederiks et al. 2015): socioeconomic characteristics, dwelling characteristics, ownership of home appliances, and geographical conditions. In addition, information about LED installation is included.

3.2. Data summary

3.2.1. Data summary

Table 1 shows the descriptive statistics by household composition and income class. On average, multiple-person households use more electricity; have higher incomes and more appliances; live in larger homes; and behave in a more eco-friendly manner than single-person households. The share of single-person households is large in the lowest-income class; approximately half of them are single-person households. Household income affects the amount of time that people stay at home; people in the low-income class spend more time at home and go out less frequently.

The table shows that household electricity consumption increases with higher income classes. The average electricity consumption of the lowest-income class is 272.68 kWh per month, while that of the highest-income class is 571.67 kWh per month. The survey contains information about the monthly electricity bill. We calculated the average electricity price by dividing the amount of the electricity bill by the amount of electricity consumption. The households in the lowest-income class pay 26.90 per kWh on average, while those in the highest-income class pay 28.13 per kWh. Hence, households in high-income classes pay a higher electricity price. This is because the block pricing scheme is used in Japan.[4] Since high-income households consume more electricity, they face a higher electricity price.

The table also shows that high-income households own more home appliances. The average household in the lowest-income class owns 1.51 units of televisions (TVs), 1.50 units of air conditioners (ACs), and 0.87 units of personal computer (PCs), while the average household in the highest-income class owns 2.58 units of TVs, 3.84 units of ACs, and 2.25 units of PCs. Households that intend to use more home appliances require a higher circuit breaker amperage capacity.[5] The basic charge for the electricity contract increases as the circuit breaker amperage capacity increases. Since high-income households own more appliances, they make contracts at a higher amperage capacity. Consequently, they face a higher electricity price.

3.2.2. Installation of LEDs

In the survey, households were asked whether they had installed LEDs in the living room, dining room, kitchen, bedroom, and other rooms. Table 2 shows the correlation of installation across rooms. The table suggests that households that install LEDs in the living room tend to install LEDs in other rooms. Due to this correlation, it is difficult to estimate the impact of LED installation for each room separately. Therefore, in the following analysis, we will concentrate on the response to LED installation in the living room.

Previous studies, such as Mills and Schleich (2010), Ameli and Brandt (2015) and Das et al. (2018), report that household income determines the likelihood of the installation of energy

[4] The unit price of electricity increases as the amount of electricity consumption increases.
[5] The contracted ampere capacity is an indication of the volume of electricity that can be used at any one time.

efficient technologies. We also find that household income determines the type of lamps installed. Figure 3.a. shows the type of lamps installed in the living room in the SCDEH. Since several varieties of lamps could be installed in the living room, multiple responses are allowed. Households respond "yes" if any corresponding lamp is installed. Therefore, the sum of the shares of incandescent, fluorescent, and LED lamps may be greater than 100% in the survey.[6] The figure shows that the most popular lamp is a fluorescent lamp; 62.3% of households answered that they installed a fluorescent lamp in the living room. In contrast, 34.7% of households installed an incandescent lamp, and only 11.4% of households installed LEDs. The figure further shows that the likelihood of LED installation increases as the income class increases. We observe a similar pattern for incandescent lamp installation; namely, high-income households install incandescent lamps more frequently. In contrast, we find the opposite pattern with regard to fluorescent lamp installation; high-income households install fluorescent lamps less frequently.

Previous studies find that the age of the household head influences the energy saving investment. In general, the likelihood of energy saving investment shows an inverse U shape. Middle-aged households invest in energy-saving technologies most frequently. However, in the case of energy-efficient lamps, Ameli and Brandt (2015) and Das et al. (2018) find that the age of the household head does not affect the likelihood of installation. In Figure 3.b., we compare the type of lamps by the age of the household head. This figure shows that the age of the household head does not determine the likelihood of LED installation. However, we find that the age of the household head determines the likelihood of the other two types of lamps; elderly households tend to use fluorescent lamps, while young households tend to use incandescent

[6] In the analysis, we use a dummy variable that takes 1 if a household uses LEDs most frequently in the living room as an LED installation variable.

lamps.

Figure 3.c. shows the relationship between the type of lamps and the construction age of houses. The figure shows that LEDs are being installed in houses built after 2011 at a rate nearly twice as high as that of houses built previously. Fluorescent lamps are the most popular type of lamp in houses built before 2011. Although the share of incandescent light bulbs has been relatively small, it increased until 2011.

Respondents to the survey were also asked about the type of the lamp most frequently used in the living room. According to the survey results, households that use LEDs most frequently consume 434.5 kWh of electricity per month. Households that use incandescent lamps most frequently consume 408.7 kWh, while households that use fluorescent lamps most frequently consume 399.1 kWh. Not surprisingly, households that consume more electricity tend to install LEDs. This finding suggests that we need to control the factors that influence household electricity usage before assessing the impact of LED installation.

4. Model

In this study, we employ Conditional Demand Analysis (CDA) to evaluate the determinants of household electricity consumption. CDA is a statistical technique for estimating the household electricity consumption of various appliances by combining survey, consumption, and weather data. CDA was developed by Parti and Parti (1980) and has been used by many scholars, including Aigner et al. (1984), LaFrance and Perron (1994), Leahy and Lyons (2010), Newsham and Donnelly (2013), and Matsumoto (2016). The model used in this study is given by

$$\ln E_{it} = \alpha + \beta LED_i + \boldsymbol{\Gamma}'\boldsymbol{X}_i + \boldsymbol{\Theta}'\boldsymbol{Z}_{it} + \omega_j + \omega_t + \varepsilon_{it} \ , \quad (1)$$

where E_{it} is household i's electricity consumption in month t. $\boldsymbol{X}_i$ is the vector of control variables composed of the socioeconomic characteristics of households, housing conditions, and the ownership of 11 varieties of home appliances, while $\boldsymbol{Z}_{it}$ is the vector of control variables that vary between sampling months (namely, the electricity price and the vacancy dummy variable). LED_i is a dummy variable that takes a value of 1 if household i answered that it uses LED most frequently in the living room. ω_j and ω_t are variables that measure regional and monthly fixed effects, respectively. Finally, ε_{it} is the error term.

5. Results

5.1. Comparison with previous research

The estimation results are presented in Table 3. Although we controlled for both regional and seasonal effects in all the models, we omitted them from Table 3 for the sake of brevity.

Before assessing the impact of LED installation, we verify the validity of our estimation results based on Model 1, which includes the data of all households. First, the sign of all appliance variables becomes positive and statistically significant. METI (2011) estimated the electricity usage of various appliances based on the 2009 data. In Figure 4, we compare the shares of electricity usage for measured appliances estimated from this estimation with those estimated from METI's study. Compared to METI's study, the SCDEH study presents a higher usage share for ACs but presents a lower usage share for refrigerators and TVs. These results seem to be consistent with the fact that from METI's survey in 2009 to the SCDEH survey in 2016, the energy efficiency of refrigerators improved and the watching time of TVs decreased, but the number of air conditioners increased.

In terms of housing variables, we obtained the expected results from previous studies:

electricity usage increases as the floor area of houses increases; households living in new houses use less electricity than those living in old houses; and households living in apartment housing use less electricity than those living in detached houses.

The results of the demographic variables are consistent with those of previous studies. Model 1 shows that electricity usage increases as the number of family member increases. Electricity consumption increases as the age of the household head increases. The presence of children between 10-19 years old increases electricity usage, while the presence of elderly persons over 75 years old decreases it.

The survey asked whether all family members spent more than 5 days outside the house. The result shows that electricity usage decreases on vacant days. The survey further asked whether someone usually stayed at home during the day on weekdays. The table shows that electricity usage increases if someone stays at home during the day on weekdays.

The income variable became positive and statistically significant in Model 1. Therefore, we find that electricity usage increases as household income increases even after controlling for appliance ownership and housing conditions. This may suggest that wealthy households use appliances more intensively than less wealthy households. According to our estimation, the income elasticity of demand is approximately 0.07.

We calculate the (average) electricity price by dividing the electricity bill by electricity consumption. We then estimate the price elasticity of electricity demand. According to our calculation presented in Model 1, the price elasticity of electricity demand is approximately 1.32. In Model 5 to Model 10, we classify households into six income classes and estimate the price elasticity for each income class. To the best of our knowledge, no previous studies controlled for the appliance ownership condition when estimating the income-level-specific price elasticity of electricity demand. The table shows that the price elasticity of the middle-income class is higher than that of the low- and high-income classes. In other words, the middle-income class is more sensitive to the price of electricity.

5.2. Effectiveness of LED installation

Table 3 presents the impact of LED installation on electricity usage. In Model 1, the LED-installation variable becomes negative and statistically significant. According to our calculation, the yearly electricity usage of households that installed LEDs in the living room is lower by 139.5 kWh than that of households without such installation. This result suggests that the average household saves approximately JPY 3766.6 annually by installing LEDs; thus, the rate of electricity saving is approximately 2.8%.

Based on the estimation by METI (2013), the expected electricity saving rate is approximately 4.3%.[7] However, the rate of electricity saving is approximately 2.8% in this survey analysis. Hence, households use the electricity saved by LED installation for the use of other appliances. The size of this rebound effect corresponds to approximately 1.5% of the total household electricity usage.

Although we focused on multi-person households in Model 4, the LED-installation variable became negative and statistically significant again. According to our calculation, the average multi-person household saves approximately JPY 6,519.2 annually. This is approximately 4.4% of electricity saving.

The LED-installation variable became insignificant in Model 3, which focused on single-person households. Similarly, the LED-installation variable became insignificant in Model 5 for the lowest-income class. Perhaps the non-significance in these two models can be explained

[7] See Appendix for the assumptions for this calculation.

by the fact that many single households in the lowest-income class are young persons, who stay home less often and use less lighting.

5.3. Robustness check: Inclusion of energy saving activities

If households that installed LEDs paid closer attention to electricity consumption, then the regression of Equation 1 would suffer from omitted variable bias. In the survey, subjects were asked whether they adjusted the brightness of lights and turned lights off frequently. We include the responses for energy saving activities to solve the omitted bias problem. Specifically, we estimate the following equation:

$$\ln E_{it} = \alpha + \beta LED_i + \boldsymbol{\Gamma}'\boldsymbol{X}_i + \boldsymbol{\Theta}'\boldsymbol{Z}_{it} + \boldsymbol{\Lambda}'\boldsymbol{ESA}_i + \omega_j + \omega_t + \varepsilon_{it}, \qquad (2)$$

where $\boldsymbol{ESB}_i$ is a vector of energy saving activity dummies. These dummy variables take a value of one if household i answered that it adjusts the brightness of lamps or switches off lights frequently.

In the survey, 55.3% of households answered that they adjusted the brightness of lights, while 81.6% of them answered that they turned lights off frequently. Therefore, the latter is more common than the former. Figure 5.a. shows the intensity of the energy saving activities of different income class households. This figure shows that middle-income households practice two types of energy saving activities more than the lowest- or highest-income households do. Figure 5.b. shows that the likelihood of engaging in energy saving activities generally increases as the age of the household head increases. Finally, Figure 5.c. presents the relationship between housing age and energy saving activities. It shows that households living in new houses are more likely to turn lights off frequently, but no systematic relationship is found between housing age and brightness adjustment.

The estimation result of Equation 2 is presented in Model 2 in Table 3. The parameter value of the LED installation in Model 2 is somewhat smaller than that in Model 1 (2.3% vs. 2.8%). This suggests that the energy saving effect of LED installation is overly estimated in Model 1.

Model 2 shows that electricity usage can be reduced by 3.1% if households adjust the brightness of lights. Furthermore, households can reduce their electricity usage by 6.8% if they switch lights off frequently. These results suggest that energy saving activities are important for energy saving.

6. Conclusions and Policy Implications

In this study, we analyzed comprehensive data on household electricity usage and evaluated the energy saving effects of LED installation and energy saving behaviors. We found that households can reduce electricity usage by 2.3%-2.8%, with an annual cost saving of approximately JPY 3047.9-3766.6. It is expected that multiple-person households can save more electricity; they can decrease electricity consumption by 3.8%-4.4% and can reduce their electric bill by JPY 5689.5-6519.2 per year.

Although we find a significant energy saving effect of LED installation, this effect is smaller than the one expected from engineering calculations. This result suggests the possibility of a rebound effect associated with LED installation. Some people may allocate the energy saving obtained from LED replacement to the usage of other home appliances. Others may leave lights on longer than before with the knowledge that LEDs use less electricity.

We also found a sizable energy saving effect through energy saving activities, as found in other Japanese studies (Arimura et al. 2018). Policies to encourage energy saving activities are crucial for the energy conservation of the residential sector in addition to policies to promote LED installation. This is an important area of energy conservation policy.

Moreover, our estimation results suggest that the price elasticities of electricity vary across households depending on income level. In particular, the estimation results suggest that middle-income households have a higher price elasticity. If this is the case, power companies can reduce electricity demand by charging a higher price to this group of households. Therefore, variation in price elasticity across households should be examined. This is an area of future research.

Acknowledgement

This research was supported by the Environment Research and Technology Development Fund (2-1707) of the Environmental Restoration and Conservation Agency.

Appendix

This appendix explains the engineering calculation of the impact of LED installation. We impose the following three assumptions in this calculation.

1. The usage of lamps remains the same after LED installation.
2. For the energy efficiencies of lamps, the values in METI (2013) are used.
3. If a household uses multiple types of lamps, we consider the lamp with the longest operating time as the lamp the household uses.

Table A.1 shows the electricity consumption of each type of lamp reported in METI (2013). The wattage of an LED lamp is more than one-fifth of the wattage of an incandescent lamp and three-quarters of the wattage of a fluorescent lamp.

Table A.2 presents the following calculated values for the engineering calculation of the replacement impact of conventional lamps with LED lamps. Electricity consumption will be reduced by 83.41% through the replacement of incandescent lamps with LED lamps, while it will be reduced by 25.35% through the replacement of a fluorescent lamp with an LED. According to the estimation by METI (2011), a typical household uses 13.4% of electricity for lighting. Therefore, the impact of the replacement of an incandescent lamp with an LED lamp on the total household electricity usage becomes $\Delta_1(\%) = 13.4 \times 0.8341$, while the impact of the replacement of a fluorescent lamp with an LED lamp becomes $\Delta_2(\%) = 13.4 \times 0.2535$.

In the SCDEH, 7.77% of households responded that they used incandescent lamps most frequently, while 58.96% of them responded that they used fluorescent lamps most frequently (Table A.1). If these two types of households are combined, approximately 66.73% of households have energy saving potential. The relative share of incandescent-lamp households is $s_1 = 7.77 \div 66.73$, while the relative share of fluorescent-lamp households is $s_2 = 58.96 \div 66.73$. Consequently, the expected energy saving from LED replacement becomes $4.3\% = s_1\Delta_1 + s_2\Delta_2$. In the text, we use this value to measure the rebound effect.

References

1. Agency for Natural Resources and Energy of Japan. 2015. Trends in final energy consumption and real GDP. Energy White Paper 2017.
2. Aigner, D.J., Sorooshian, C., and Kerwin, P. 1984. Conditional demand analysis for estimating residential end-use load profiles. *The Energy Journal*, 5(3): 81–97.
3. Ameli, N. & Brandt, N. 2015. Determinants of households' investment in energy efficiency and renewables: evidence from the OECD survey on household environmental behavior and attitudes. Environmental Research Letters, 10(4). http://iopscience.iop.org/1748-9326/10/4/044015.

4. Arimura, T. H. Iwata,K. Katayama,H. & Sakudo,M. 2018 “Seemingly Unrelated Interventions: Environmental Management Systems in the Workplace and Energy Conservation Behaviors at Home,” RIEEM Discussion Paper Series 1802, Research Institute for Environmental Economics and Management, Waseda University.
5. Chitnis, M. & Sorrell, S. 2015. Living up to expectations: Estimating direct and indirect rebound effects for UK households. Energy Economics, 52(S1): 100–116. DOI: 10.1016/j.eneco.2015.08.026.
6. Chitnis, M., Sorrell, S., Druckman, A., Firth, S.K., & Jackson, T. 2013. Turning lights into flights: Estimating direct and indirect rebound effects for UK households. Energy Policy, 55(C): 234–250. DOI: 10.1016/j.enpol.2012.12.008.
7. Das, R., Richman, R., & Brown, C. 2018. Demographic determinants of Canada’s households’ adoption of energy efficiency measures: observations from the Households and Environment Survey, 2013. Energy Efficiency, 11(2): 465–482. DOI: 10.1007/s12053-017-9578-4.
8. Dick, R.R. 2016. Which countries have banned incandescent lightbulbs? Quora. (27 July 2016) <https://www.quora.com/Which-countries-have-banned-incandescent-lightbulbs> (accessed on 17 February 2018)
9. European Commission. 2009. Phasing out conventional incandescent bulbs. (1 September 2009) <http://europa.eu/rapid/press-release_MEMO-09-368_en.htm> (accessed on 17 February 2018)
10. Federation of Power Electric Companies of Japan. 2015. <http://www.fepc.or.jp/library/data/ index.html> (accessed on 20 February 2018)
11. Frederiks, E.R., Stenner, K, & Hobman, E.V. 2015. The socio-demographic and psychological predictors of residential energy consumption: A Comprehensive Review.

Energies, 8: 573–609. DOI: 10.3390/en8010573.

12. Gillingham, K., Newell, R.G., & Palmer, K. 2009. Energy efficiency economics and policy. NBER Working Paper No. 15031. <http://www.nber.org/papers/w15031> (accessed on 19 February 2018)
13. Gram-Hanssen, K. 2013. Efficient technologies or user behavior, which is the more important when reducing households' energy consumption? Energy Efficiency, 6(3): 447–457. DOI: 10.1007/s12053-012-9184-4.
14. Greening, L.A., Greene, D.L., & Difiglio, C. 2000. Energy efficiency and consumption—the rebound effect—a survey. Energy Policy, 28: 389–401. DOI: 10.1016/S0301-4215(00)00021-5.
15. Hickman, L. 2012. Light goes out for incandescent bulbs: Phased ban on the sale of incandescent lightbulbs is completed following EU directive to reduce energy use of lighting. (31 Aug 2012) The Guardian. <https://www.theguardian.com/environment/2012/aug/31/lightbulbs-incandescent-europe> (accessed on 20 February 2018)
16. International Energy Agency. 2016. Energy Efficiency Indicators 2016.
17. Institute of Energy Economics of Japan. 2015. Energy and Economic Statistics Catalog.
18. Inoue, N. & Matsumoto, S. 2017. Did improvement of home appliance energy efficiency lead to a reduction of household electricity usage? Experience from the Japanese Top Runner Program. Paper presented at The 16th International Conference of the Japan Economic Policy Association. Okinawan, Japan. (4 November 2017).
19. Japan Lighting Manufacturers Association. 2018. Voluntary Survey. <http://jlma.or.jp/tokei/index.htm> (accessed on 23 July 2018)
20. Jevons, W.S. (1865 [1965]) The Coal Question, 3rd edition. Augustus M. Kelley, New York.
21. Karlin, B., Davis, N., Sanguinetti, A. Gamble, K., Kirkby, D., & Stokols, D. 2014.

Dimensions of conservation: exploring differences among energy behaviors. Environment and Behavior, 46(4): 423–452. DOI: 10.1177/0013916512467532.

22. LaFrance, G. and Perron, D. 1994. Evolution of residential electricity demand by end-use in Quebec 1979–1989: A conditional demand analysis. Energy Studies Review 6(2): 164–173. DOI: 10.15173/esr.v6i2.334.
23. Leahy, E. and Lyons, S. 2010. Energy use and appliance ownership in Ireland. Energy Policy, 38: 4265–4279. DOI: 10.1016/j.enpol.2010.03.056.
24. Lightbulbs Direct Ltd. 2018. The light bulb ban - When did it take effect and what does it cover? <https://www.lightbulbs-direct.com/article/the-light-bulb-ban/> (accessed on 17 February 2018)
25. Matsumoto, S. 2015. Environmental Subsidies as a Policy Instrument: How did they work in the Japanese market? Routledge, Taylor & Francis Group.
26. Matsumoto, S. 2016. Electric appliance ownership and usage: Application of conditional demand analysis to Japanese household data. Energy Policy, 94, 214–223. DOI: 10.1016/j.enpol.2016.03.048.
27. Ministry of the Environment of Japan. 2016. Survey on the carbon dioxide emissions from households.
28. Ministry of Economy, Trade, and Industry. 2011. Paper prepared for Energy Efficiency Standards Subcommittee, Advisory Committee for Natural Resources and Energy. <http://www.meti.go.jp/committee/summary/0004310/017_s01_00.pdf> (accessed on 12 June 2018)
29. Ministry of Economy, Trade, and Industry. 2013. Final Report for Working Group on Classification Standards for Luminaires, etc., New and Renewable Energy Subcommittee, Committee on Energy Efficiency and Renewable Energy, Advisory Committee for Natural

Resources and Energy. <http://www.meti.go.jp/committee/sougouenergy/shoene_shinene/sho_ene/shomeikigu/pdf/report01_01_00.pdf> (accessed on 12 June 2018)

30. Mills, B.F. & Schleich, J. 2010. Why don't households see the light? Explaining the diffusion of compact fluorescent lamps. Resource and Energy Economics, 32(3), 363–378. DOI: 10.1016/j.reseneeco.2009.10.002.

31. Nadel, S. 2012. The rebound effect: Large or small. An ACEEE White Paper. American Council for an Energy-Efficient Economy.

32. Nair, G., Gustavsson, L., & Mahapatra, K. 2010. Factors influencing energy efficiency investments in existing Swedish residential buildings. Energy Policy, 38, 2956–2963. DOI: 10.1016/j.enpol.2010.01.033.

33. Newsham, G.R. & Donnelly, C.L. 2013. A model of residential energy end-use in Canada: Using conditional demand analysis to suggest policy options for community energy planners. Energy Policy 59, 133–142. DOI: 10.1016/j.enpol.2013.02.030.

34. Nippon Television. 2015. Strict energy saving standard from fluorescent lamps to LED. Nitelenews 24. (26 November 2015) <http://www.news24.jp/articles/2015/11/26/06315839. html> (accessed on 17 February 2018)

35. Parti, M. and Parti, C. 1980. The total and appliance-specific conditional demand for electricity in the household sector. Bell Journal of Economics, 11(1), 309–321.

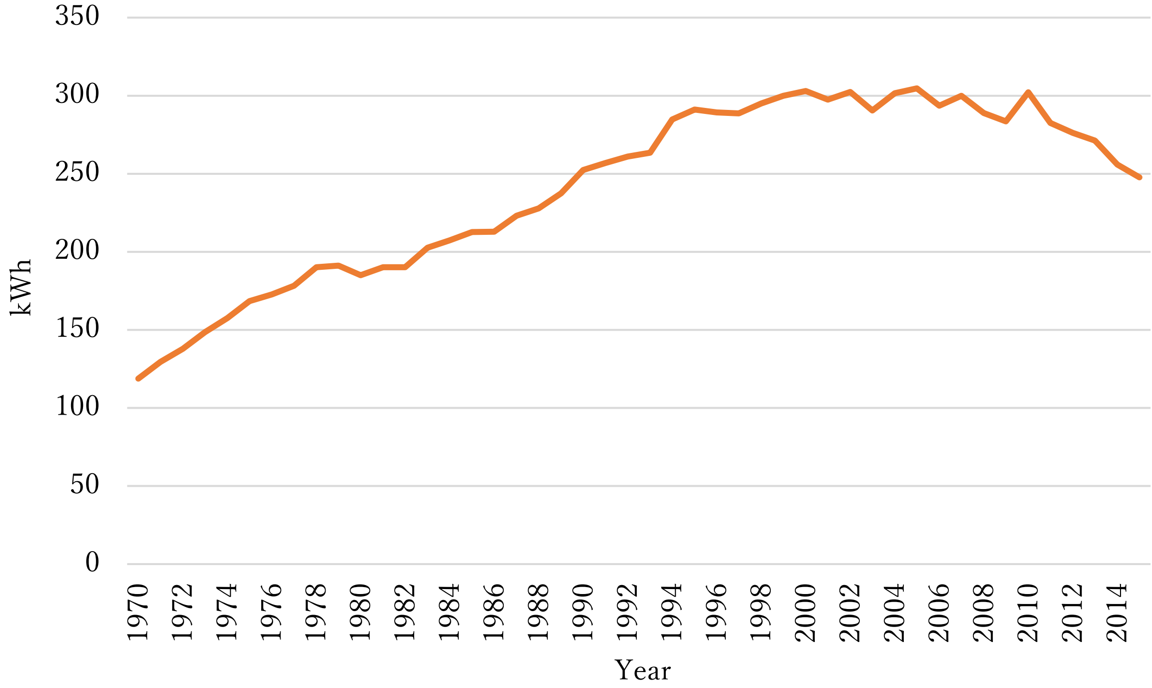
36. Poortinga, W., Steg, L., Vlek, C., and Wiersma, G. 2003. Household preferences for

37. energy-saving measures: A conjoint analysis. Journal of Economic Psychology, 24, 49–64. DOI: 10.1016/S0167-4870(02)00154-X.

38. US Department of Energy. 2012. New lighting standards began in 2012. <https://energy.gov/energysaver/save-electricity-and-fuel/lighting-choices-save-you-money/new-lighting-standards-began> (accessed on 17 February 2018)

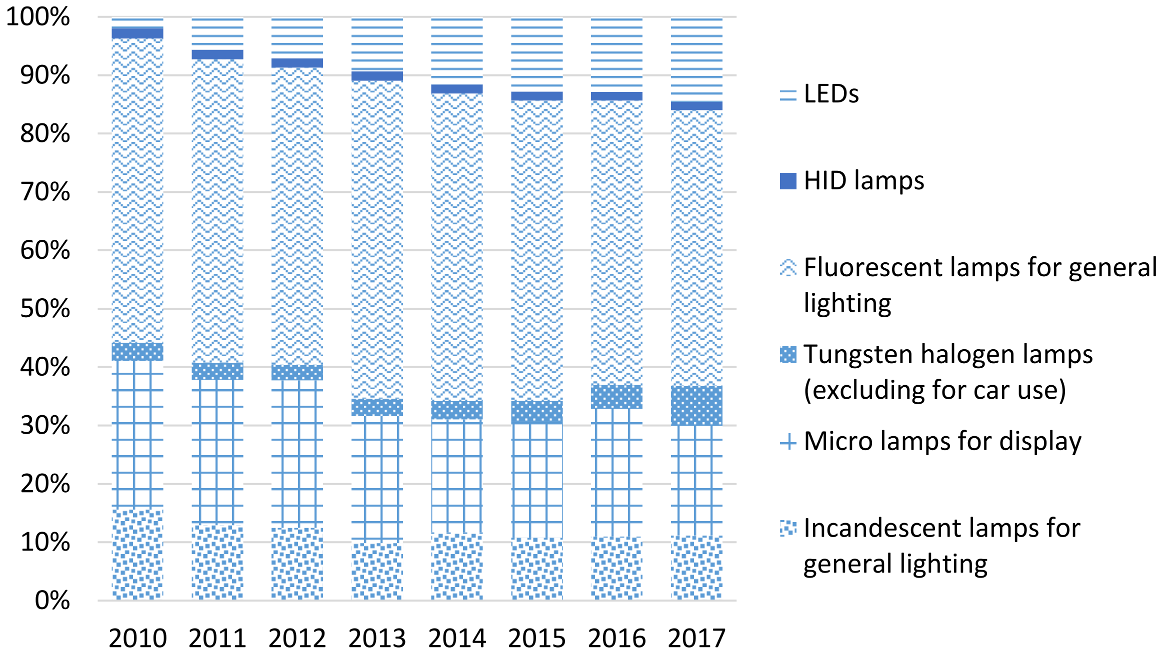
39. US Department of Energy. 2015. LED lighting. <https://energy.gov/energysaver/save-electricity-and-fuel/lighting-choices-save-you-money/led-lighting> (accessed on 17 February 2018)
40. US Environmental Protection Agency. 2011. How the Energy Independence and Security Act of 2007 affects light bulbs: Inefficient light bulbs are being phased out. <https://www.epa.gov/ cfl/how-energy-independence-and-security-act-2007-affects-light-bulbs> (accessed on 17 February 2018)

Figure 1. Change in electricity usage of the average Japanese household



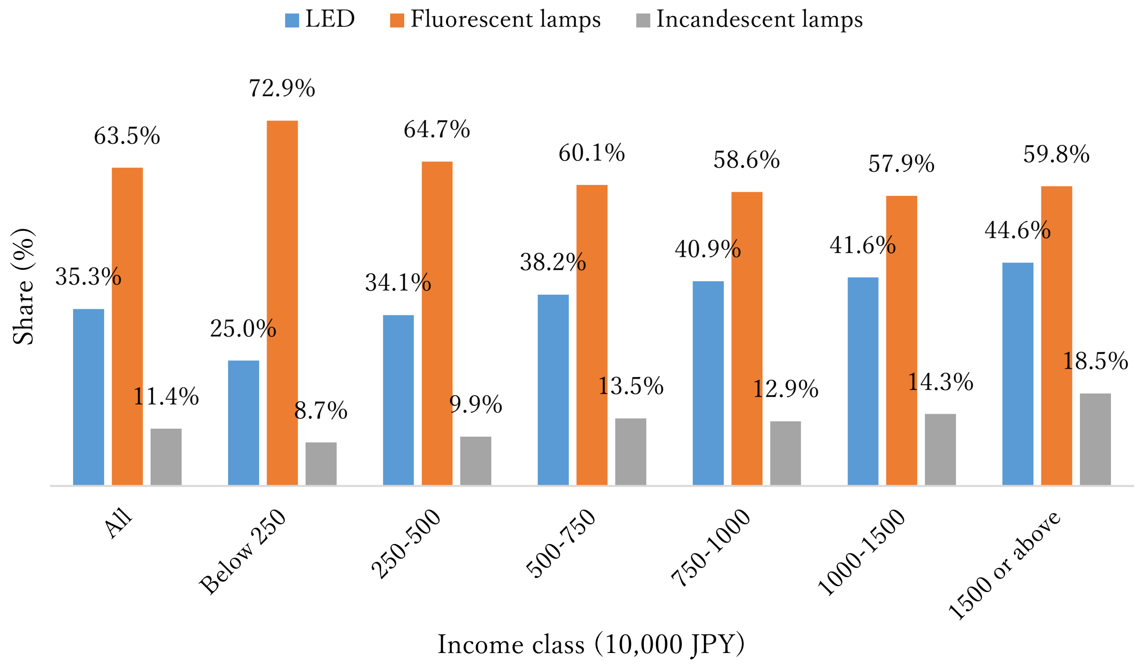
Source: Federation of Electric Power Companies of Japan (2015)

Figure 2. Change in the share of the shipment quantity of lamps



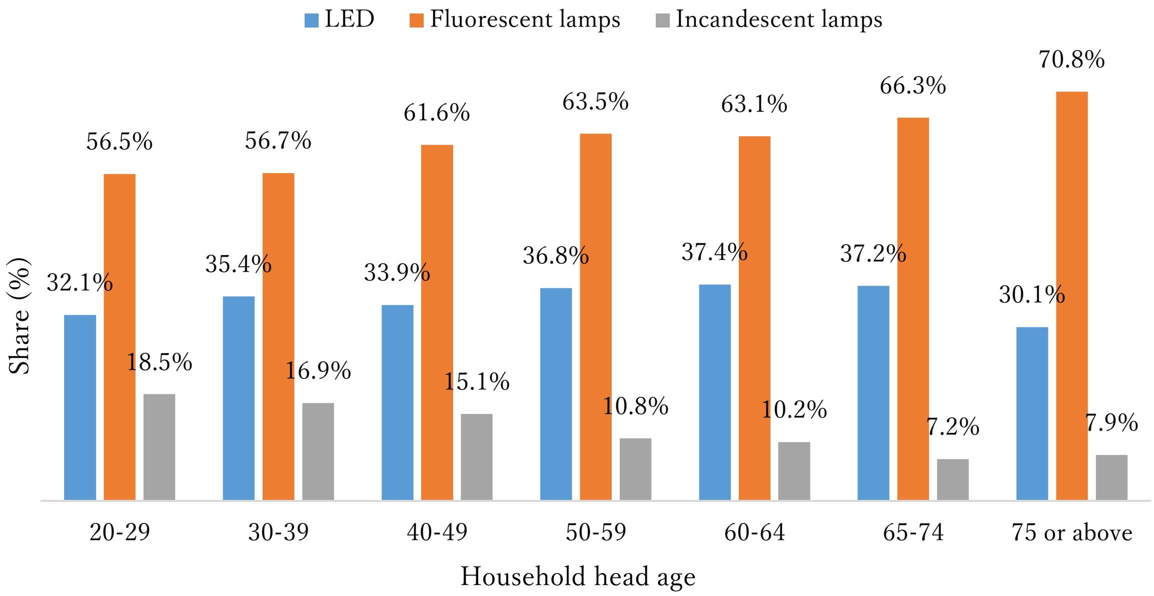
Source: Japan Lighting Manufacturers Association (2017)

Figure 3.a. Type of living room lamps by income class



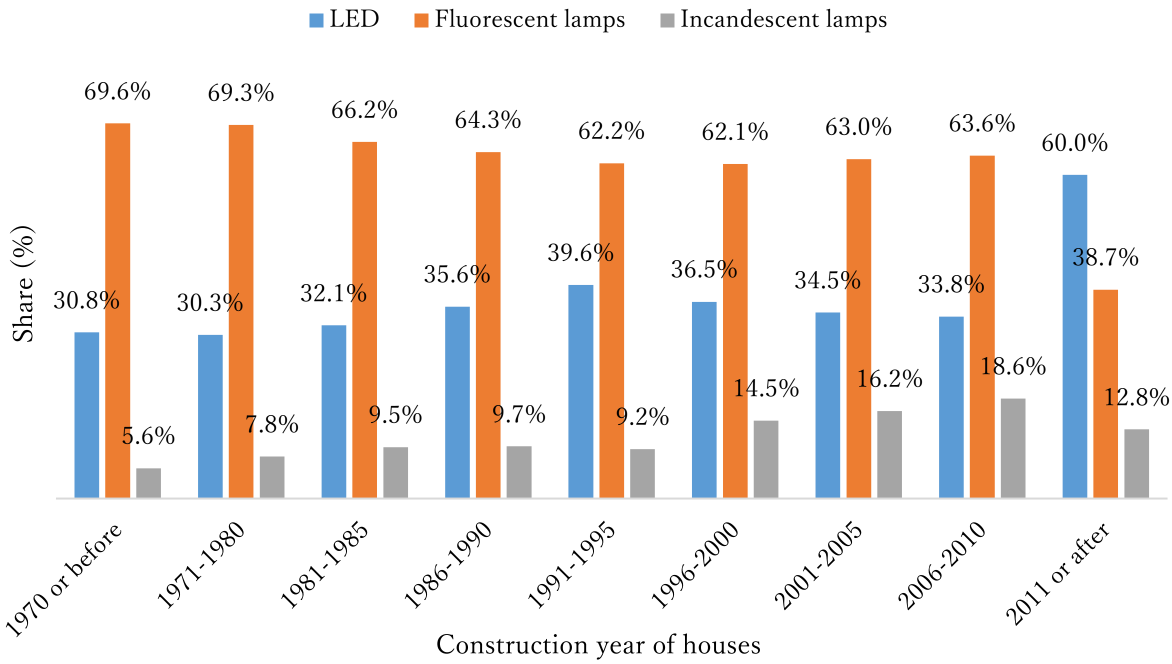
Note. Multiple responses are allowed. Therefore, the total is not 100%.
Data Source: Survey on Carbon Dioxide Emission from Households (Ministry of the Environment of Japan, 2016).

Figure 3.b. Type of living room lamps by household head age



Note. Multiple responses are allowed. Therefore, the total is not 100%.
Data Source: Survey on Carbon Dioxide Emission from Households (Ministry of the Environment of Japan, 2016).

Figure 3.c. Type of living room lamps by construction age of houses



Note. Multiple responses are allowed. Therefore, the total is not 100%

Data Source: Survey on Carbon Dioxide Emission from Households (Ministry of the Environment of Japan, 2016).

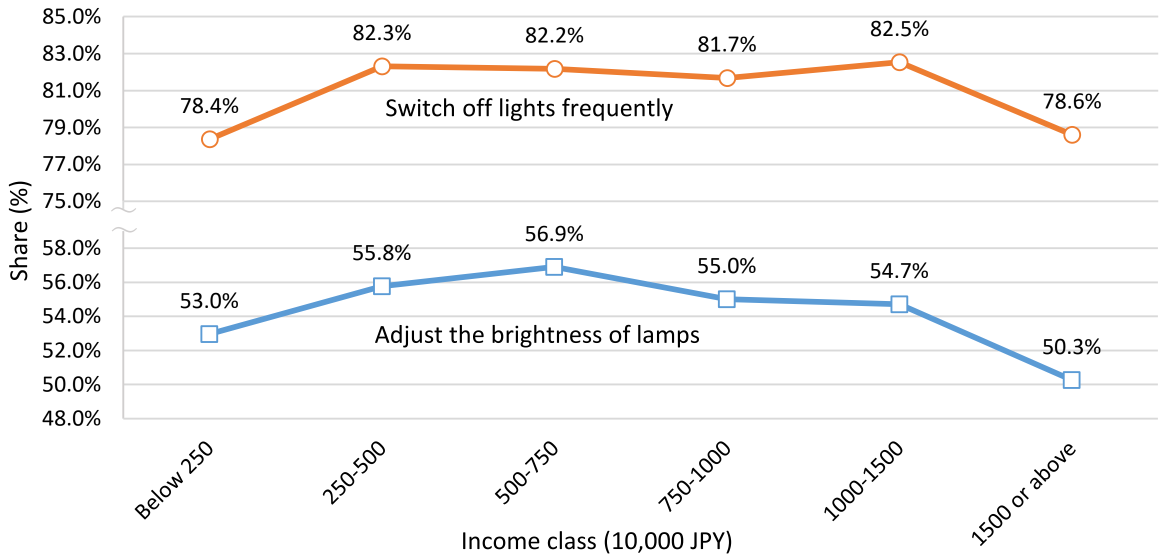
.

Figure 4. The share of electricity usage of appliances

	Our estimate	2009 estimate*
Air Conditioner	13.4%	7.4%
Refrigerator	12.3%	14.2%
Microwave & oven	4.8%	1.8%
Electronic bidet	4.8%	3.7%
Television	4.5%	8.9%
Dishwasher with dryer	3.0%	3.7%
Personal computer	2.9%	2.5%
Electric pot	1.7%	3.2%
Humidifier	1.4%	-
DVD player	1.4%	1.6%
Air cleaner	1.1%	-

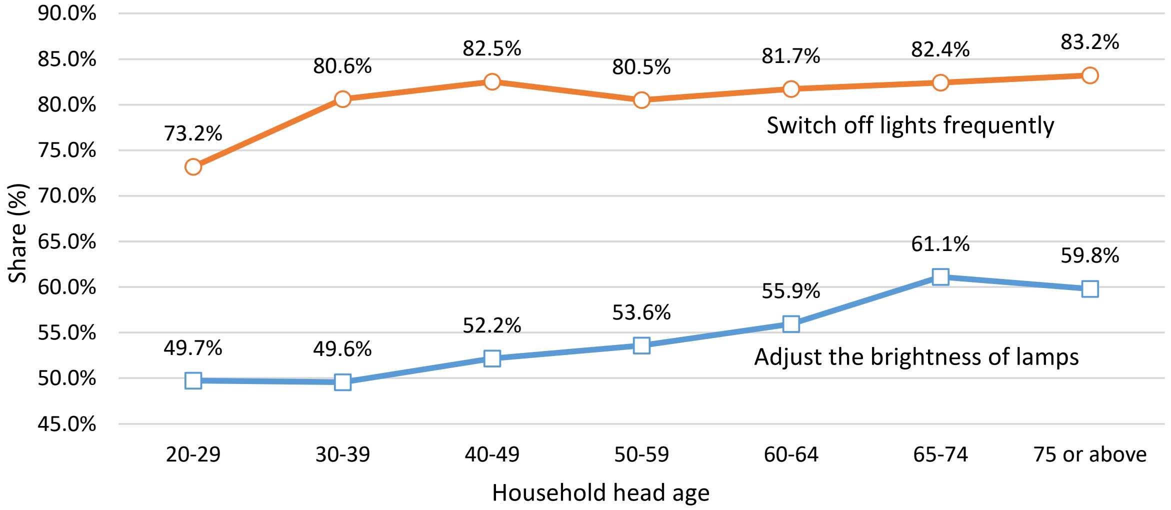
*Source: Ministry of Economy, Trade and Industry (2011)

Figure 5.a. Energy saving activities by income class



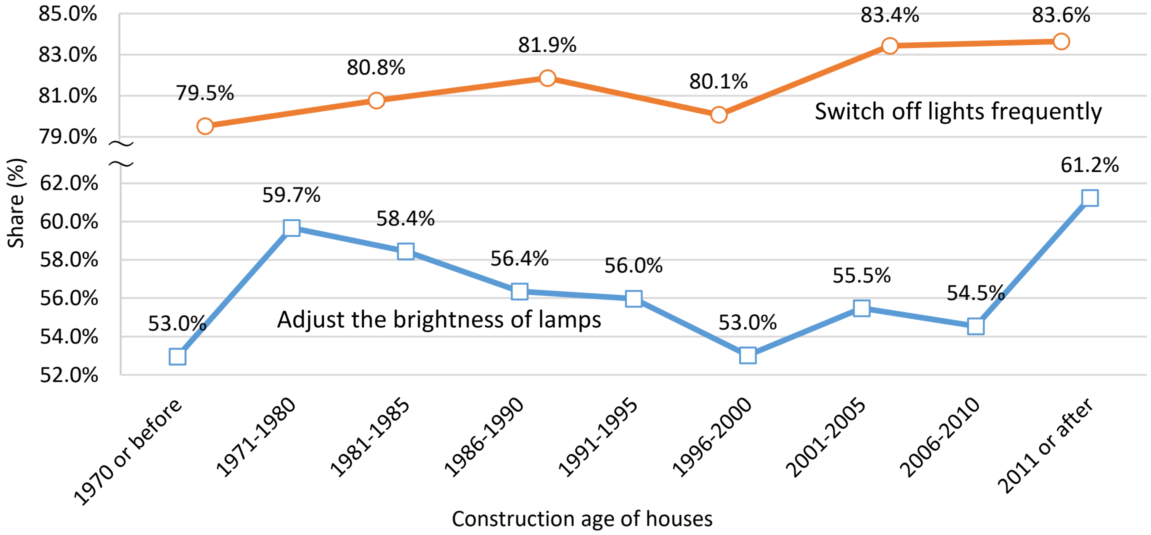
Data Source: Survey on Carbon Dioxide Emission from Households (Ministry of the Environment of Japan, 2016)

Figure 5.b. Energy saving activities by household head age



Data Source: Survey on Carbon Dioxide Emission from Households (Ministry of the Environment of Japan, 2016)

Figure 5.c. Energy saving activities by construction age of houses



Data Source: Survey on Carbon Dioxide Emission from Households (Ministry of the Environment of Japan, 2016)

Table 1. Descriptive statistics

Variable	Unit	All households	Single-person	Multiple-person	Income class (10,000 JPY) < 250	250-500	500-750	750-1000	1000-1500	> 1500
Electricity usage variables										
Electricity usage per month	kWh	411.07	212.36	454.37	272.68	376.69	452.64	492.43	527.23	571.67
Electricity price	JPY/kWh	26.64	27.04	26.56	26.90	26.74	26.22	26.50	26.72	27.84
Energy saving behaviors										
Installation of LED light bulb (living room)	dummy[a]	0.35	0.26	0.37	0.25	0.34	0.38	0.41	0.42	0.45
Switch off lights frequently	dummy[a]	0.55	0.47	0.57	0.53	0.56	0.57	0.55	0.55	0.50
Adjust the brightness of lamps	dummy[a]	0.82	0.77	0.83	0.78	0.82	0.82	0.82	0.83	0.79
Demographic variables										
Income	10^4 JPY	560.04	322.70	611.51						
Number of persons	persons	2.80	1.00	3.20	1.74	2.62	3.19	3.38	3.55	3.57
Share of single-person households	0-1	0.18	1.00	0.00	0.53	0.16	0.09	0.06	0.04	0.06
Age of household head	years	56.67	56.38	56.73	61.85	57.62	52.75	53.68	54.47	57.20
Presence of children 10-19 years old	dummy[a]	0.21	0.00	0.25	0.07	0.15	0.28	0.33	0.32	0.23
Presence of elderly person over 75 years old	dummy[a]	0.18	0.13	0.19	0.22	0.19	0.14	0.15	0.18	0.19
Stay at home on weekdays in daytime	dummy[a]	0.57	0.39	0.61	0.64	0.60	0.52	0.49	0.51	0.53
Vacancy of house more than 5 days during the month	dummy[a]	0.02	0.01	0.05	0.02	0.02	0.02	0.02	0.02	0.01
Appliance ownership										
Television	unit	1.96	1.24	2.12	1.51	1.88	2.02	2.24	2.30	2.58
Refrigerator	unit	1.24	1.08	1.28	1.17	1.22	1.23	1.28	1.33	1.56
Air Conditioner	unit	2.32	1.35	2.53	1.50	2.11	2.42	2.82	3.22	3.84
Dishwasher with dryer	unit	0.28	0.08	0.32	0.10	0.22	0.35	0.40	0.48	0.52
Microwave & oven	unit	1.02	0.95	1.04	0.97	1.01	1.03	1.06	1.06	1.14
Electronic bidet	unit	0.89	0.52	0.97	0.54	0.82	0.97	1.10	1.21	1.39
Electric pot	unit	0.55	0.48	0.56	0.51	0.55	0.54	0.57	0.56	0.61
Humidifier	unit	0.35	0.19	0.38	0.17	0.31	0.41	0.44	0.46	0.65
Air cleaner	unit	0.42	0.24	0.46	0.24	0.38	0.48	0.52	0.57	0.70
Personal computer	unit	1.41	0.96	1.50	0.87	1.28	1.53	1.75	1.94	2.25
DVD player	unit	1.01	0.66	1.09	0.63	0.93	1.14	1.25	1.29	1.54

Table 1 continued

Variable	Unit	All households	Single-person	Multiple-person	Income class (10,000 JPY) < 250	250-500	500-750	750-1000	1000-1500	> 1500
Housing condition										
Apartment house	dummy[a]	0.31	0.58	0.26	0.40	0.32	0.31	0.28	0.25	0.28
Construction after 2011	dummy[a]	0.08	0.06	0.08	0.04	0.07	0.11	0.10	0.10	0.10
Floor area	m^2	113.54	80.08	120.80	92.75	109.61	112.99	125.70	134.61	154.61
Number of samples (households*months)	Max.	139,584	24,972	114,612	21,636	44,050	29,160	19,068	9,684	2,244
	Min.	138,275	24,779	113,496	21,466	43,655	28,885	18,860	9,602	2,225
Number of household samples	Max.	11,632	2,081	9,551	1,803	3,671	2,430	1,589	807	187
	Min.	10,487	1,728	8,618	1,546	3,377	2,288	1,460	737	164

Note. a. 1 = yes.

Table 2. Correlation of LED installation across rooms

	Living room	Dining room	Kitchen	Bed room	Other room
Living room	1				
Dining room	0.673	1			
Kitchen	0.428	0.549	1		
Bedroom	0.480	0.460	0.432	1	
Other room	0.280	0.293	0.311	0.371	1

Table 3. The impact of LED installation

	All households		Single-person	Multiple-person	< 250	250-500	500-750	750-1000	1000-1500	> 1500
Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Installation of LED light bulb	-0.028***	-0.023**	0.039	-0.044***	0.003	-0.045***	-0.020	-0.062***	-0.006	-0.061
(living room)	(0.009)	(0.009)	(0.026)	(0.009)	(0.029)	(0.015)	(0.017)	(0.020)	(0.031)	(0.069)
Adjust the brightness of lamps		-0.031***								
		(0.009)								
Switch off lights frequently		-0.068***								
		(0.011)								
Ln(Electricity price)	-1.316***	-1.313***	-1.391***	-1.319***	-1.229***	-1.346***	-1.383***	-1.337***	-1.288***	-1.027***
	(0.034)	(0.034)	(0.096)	(0.032)	(0.111)	(0.054)	(0.049)	(0.060)	(0.076)	(0.166)
Apartment house	-0.129***	-0.129***	-0.139***	-0.113***	-0.173***	-0.148***	-0.105***	-0.105***	-0.050	-0.199**
	(0.013)	(0.013)	(0.034)	(0.013)	(0.039)	(0.021)	(0.023)	(0.029)	(0.046)	(0.085)
Construction after 2011	-0.115***	-0.115***	-0.048	-0.126***	-0.063	-0.054*	-0.101***	-0.160***	-0.276***	-0.290**
	(0.018)	(0.018)	(0.042)	(0.019)	(0.057)	(0.030)	(0.031)	(0.037)	(0.050)	(0.121)
Floor area	0.104***	0.106***	0.051*	0.082***	0.059*	0.098***	0.103***	0.067**	0.149***	0.230**
	(0.014)	(0.014)	(0.030)	(0.014)	(0.033)	(0.021)	(0.026)	(0.030)	(0.050)	(0.088)
Ln(income)	0.066***	0.066***	0.044**	0.040***						
	(0.008)	(0.008)	(0.018)	(0.008)						
Age of household head	0.004***	0.004***	0.005***	0.003***	0.004***	0.005***	0.005***	0.003***	0.002	-0.001
	(0.000)	(0.000)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.002)	(0.004)
Presence of children (10-19	0.027**	0.026**		0.042***	0.005	0.031	0.036*	0.035	0.029	0.130*
years)	(0.013)	(0.013)		(0.012)	(0.061)	(0.023)	(0.020)	(0.026)	(0.036)	(0.076)
Presence of elderly person (>	-0.040***	-0.041***	0.003	-0.019	-0.025	-0.014	-0.038	-0.056	-0.001	-0.002
75 years)	(0.013)	(0.013)	(0.043)	(0.014)	(0.035)	(0.020)	(0.025)	(0.034)	(0.047)	(0.111)
Number of persons	0.117***	0.118***		0.085***	0.186***	0.128***	0.101***	0.106***	0.062***	0.076***
	(0.005)	(0.005)		(0.005)	(0.017)	(0.008)	(0.008)	(0.011)	(0.014)	(0.027)
Stay at home on weekdays in	0.047***	0.050***	0.050*	0.024**	0.060**	0.040***	0.033*	0.057***	0.052	0.135**
daytime	(0.009)	(0.009)	(0.026)	(0.010)	(0.027)	(0.015)	(0.017)	(0.021)	(0.034)	(0.059)
Vacancy of house more than 5	-0.219***	-0.218***	-0.201***	-0.175***	-0.168***	-0.263***	-0.186***	-0.215***	-0.252***	-0.187*
days during the month	(0.017)	(0.017)	(0.027)	(0.019)	(0.040)	(0.031)	(0.032)	(0.041)	(0.068)	(0.106)

Table 3 continued

Variables	All households (1)	(2)	Single-person (3)	Multiple-person (4)	< 250 (5)	250-500 (6)	500-750 (7)	750-1000 (8)	1000-1500 (9)	> 1500 (10)
Television	0.023***	0.022***	0.014	0.027***	0.022	0.006	0.038***	0.030***	0.031*	0.015
	(0.005)	(0.005)	(0.019)	(0.005)	(0.019)	(0.008)	(0.010)	(0.011)	(0.018)	(0.031)
Refrigerator	0.099***	0.097***	0.212***	0.102***	0.153***	0.136***	0.101***	0.093***	-0.002	0.119**
	(0.012)	(0.012)	(0.034)	(0.012)	(0.036)	(0.014)	(0.016)	(0.022)	(0.053)	(0.046)
Air conditioner	0.058***	0.058***	0.101***	0.055***	0.080***	0.063***	0.051***	0.063***	0.062***	0.039*
	(0.004)	(0.004)	(0.013)	(0.004)	(0.013)	(0.006)	(0.007)	(0.008)	(0.012)	(0.021)
Dishwasher with dryer	0.109***	0.110***	0.047	0.109***	0.112***	0.119***	0.100***	0.082***	0.134***	0.119**
	(0.011)	(0.011)	(0.037)	(0.011)	(0.035)	(0.018)	(0.018)	(0.024)	(0.029)	(0.055)
Microwave & oven	0.047**	0.048**	0.134**	0.0311	0.076	0.100***	0.061	0.019	0.041	-0.169*
	(0.020)	(0.021)	(0.054)	(0.019)	(0.059)	(0.036)	(0.038)	(0.036)	(0.063)	(0.092)
Electronic bidet	0.054***	0.055***	0.123***	0.046***	0.068***	0.059***	0.041***	0.055***	0.056**	0.081*
	(0.007)	(0.007)	(0.022)	(0.007)	(0.022)	(0.012)	(0.013)	(0.017)	(0.025)	(0.045)
Electric pot	0.032***	0.032***	0.007	0.034***	0.021	0.044***	0.035**	0.022	0.006	0.057
	(0.008)	(0.008)	(0.021)	(0.008)	(0.022)	(0.013)	(0.015)	(0.019)	(0.025)	(0.061)
Humidifier	0.041***	0.042***	0.062**	0.042***	0.075***	0.044***	0.047***	0.032**	0.050**	-0.007
	(0.007)	(0.007)	(0.027)	(0.007)	(0.027)	(0.013)	(0.013)	(0.015)	(0.022)	(0.031)
Air cleaner	0.025***	0.025***	0.062***	0.016**	0.053**	0.032***	0.035***	0.005	-0.030	0.022
	(0.007)	(0.007)	(0.021)	(0.007)	(0.023)	(0.011)	(0.012)	(0.013)	(0.019)	(0.035)
Personal computer	0.020***	0.020***	0.075***	0.015***	0.027*	0.032***	0.017**	0.013	0.010	0.014
	(0.005)	(0.005)	(0.018)	(0.005)	(0.015)	(0.009)	(0.008)	(0.010)	(0.013)	(0.021)
DVD player	0.014***	0.015***	0.042**	0.009	0.019	0.014	0.021**	0.011	-0.004	-0.020
	(0.005)	(0.005)	(0.016)	(0.006)	(0.017)	(0.010)	(0.011)	(0.012)	(0.019)	(0.042)
Constant	7.958***	8.006***	8.193***	8.442***	7.964***	8.326***	8.593***	8.722***	8.530***	7.613***
	(0.132)	(0.130)	(0.362)	(0.134)	(0.405)	(0.205)	(0.211)	(0.259)	(0.359)	(0.667)
Observations	101,751	101,525	16,773	84,978	15,923	35,128	24,682	16,128	8,058	1,832
# of households	8,551	8,532	1,406	7,145	1,335	2,950	2,076	1,359	677	154
Adjusted R^2	0.601	0.603	0.475	0.549	0.504	0.574	0.613	0.608	0.560	0.674

Note: *** p<0.01, ** p<0.05, * p<0.1. Robust standard errors in parentheses. Regional and monthly dummies are included in the analysis.

Table A.1 Performance of each type of lamp

	Incandescent	Fluorescent	LED*
Wattage (W)	54	12	9.4
Lumens (lm)	810	810	850
Efficiency (lm/W)	15	67.5	90.4
Share of the most frequently used lamp in the living room (%)	7.77	58.96	31.64

Note. The sum of the shares of incandescent, fluorescent, and LED lamps is below 100% because 1.62% of households responded that they used “other lamps” or unknown.”

* We report the actual performance values of LEDs shipped in 2011. METI (2013) also provides the target values of more efficient LEDs for 2017. We employ the actual performance values in 2011 as somewhat conservative values because we consider that households were using slightly older LED lamps at the time of the survey.

Data Source: Ministry of Economy, Trade and Industry (2013)

Table A.2 Engineering calculation of the impact of replacement by LED

	Incandescent - LED	Fluorescent – LED
Reduction rate by replacement (r, %)[a]	83.41	25.35
	Δ_1	Δ_2
Electricity saving rate (Δ, %)	11.18	3.40
	s_1	s_2
Relative share (s)[b]	0.12	0.88
	$s_1\Delta_1$	$s_2\Delta_2$
Potential reduction ($s\times\Delta$)	1.30	3.00
Total potential reduction ($s_1\Delta_1+s_2\Delta_2$)	4.30	

a. Data Source: Ministry of Economy, Trade and Industry (2013)

b. Data Source: Survey on Carbon Dioxide Emission from Households (Ministry of the Environment of Japan, 2016)