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Residential electricity demand in Taiwan: Consumption behavior and rebound effect

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ABSTRACT

The residential electricity demand in Taiwan was investigated using survey data of 7677 households between 2014 and 2017. Right-skewed regression models were employed to study key determinants affecting the household and appliance-specific electricity consumption. Appliances covered air conditioner, lighting, television, and refrigerator. The difference of electricity consumption between appliances with and without energy efficiency label was also studied; thus rebound effects were obtained. The estimated results indicate that household income, indoor floor area, and owning the house had positive influences on electricity consumption. Electricity consumption behavior was different among age groups and appliances. Moreover, rebound effect was large for air conditioner and refrigerator in Taiwan.

1. Introduction

Electricity consumption behavior is the results from individual decisions, which is often driven by external factors such as socioeconomic conditions, demographics, and regulations. Identifying these factors and their contributions in determining energy demand is important to affect consumption behavior and make it more energy efficient. The national goal of Taiwan is reducing greenhouse gas emissions by 20% from 2005 to 2030, based on the Executive Yuan.[1] To achieve this goal, understanding energy consumption behavior and related determinants is the first step. Then the policy makers have force points to manage the growing energy demand.

The growing economy and population increased the electricity consumption in Taiwan (Su, 2018), but the improving electrical efficiency decreased the growth rate. The electrical efficiency[2] in Taiwan had improved by approximately 15.4% from 2001 to 2016, according to the Bureau of Energy (BOE). In Fig. 1, electricity consumption in Taiwan increased annually by 1.26% in the post-financial crisis period from 2010 to 2016. In the same period, the growth rate of residential electricity consumption in Taiwan was 1.5%, higher than the aggregated one. This annual growth rate between 2001 and 2007 was 4.89% for aggregation and 4.39% for residential sector. In other words, even though the electrical efficiency has been improved, residential electricity consumption grew faster than other sectors in recent years. Addressing to the faster growth of residential electricity demand, this study finds out key determinants, such as income, indoor floor area, ownership of house, or residents' age, which affect the demand in the micro level. In addition, separating this demand into appliances can focus on the appliance-specific electricity consumption behavior and related affecting factors.

Energy efficiency (EE) is key to ensuring a safe, reliable, affordable and sustainable energy system for the future, based on International Energy Agency (IEA). One of the important EE measures in Taiwan was promoting EE label since 2001. Application with EE label was officially recognized as higher energy efficiency. However, higher EE does not necessarily represent less electrical power will be consumed, because consumers tend to consume more electricity due to economic benefit from efficiency improvement. Thus, the difference of electricity consumption between appliance with and without EE label was investigated in this study. Compared the actual saving to theoretical expected saving, the appliance-specific rebound effects were also studied.

Data came from a questionnaire survey of household electricity consumption in Taiwan. The data covered 7677 households from 2014 to 2017. The micro-level household data reveal more information of appliance-specific electricity consumption, dwelling condition, and socioeconomic status. These data are ideal for studying the electricity

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[1] The Executive Yuan is the executive branch of Taiwan government, headed by the premier who is directly appointed by the president. The Bureau of Energy (BOE) is the administrative agency under the Ministry of Economic Affairs which is under the Executive Yuan.

[2] The improvement of electrical efficiency is measured according to the negative change of electrical intensity. The electrical intensity is often used and easily available based on International Energy Agency (IEA, 2017).

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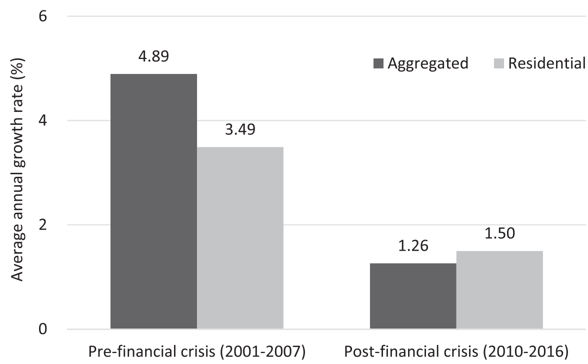

Fig. 1. Average annual growth rates of electricity consumption in Taiwan.

consumption behavior, instead of macro data. Moreover, questions addressing to the EE label of each appliance are key index to separate the different electricity consumption behavior between using high EE and general appliances; thus, the actual electricity saving due to the improvement of EE can be studied.

Household electricity consumption is a non-negative integer and had a right-skewed distribution based on the dataset. As the result, Poisson and negative binomial regression models were employed to fit the data and avoid the estimation bias due to incorrect assumption of distribution. Estimated results indicate that household income, indoor floor area, and owning the house had positive influences on electricity consumption. Electricity consumption behavior was different among age groups and appliances. Moreover, the rebound effect was significantly large for air conditioner and refrigerator, representing households change their consumption behavior and save little electricity when using these appliances with EE label. This effect was small for lighting and television so using these appliances with EE label can actually save electricity.

The remainder of this paper is organized as follows: Section 2 presents the background of residential electricity consumption in Taiwan, and introduces the endorsement label of energy efficient appliances and rebound effect. Section 3 introduces the Poisson and negative binomial regression models. Data from the questionnaire survey of residential energy consumption are presented in Section 4. Section 5 reports the estimated results of household electricity consumption and appliance-specific rebound effect. Finally, Section 6 concludes this paper.

2. Background

2.1. Residential electricity consumption

Starting from Houthakker (1951), vast research modeled the electricity demand in the residential sector. Different approaches were employed to adapt to different types of data. Regression models were often used to deal with cross sectional data (Lariviere and Lafrance, 1999), especially for the one-off household survey (Filippini and Pachauri, 2004; Lijesen, 2007; Yoo et al., 2007). Even though collecting household data costs more time and money compared to aggregated data, it was in widespread used in recent research to provide detailed estimates of micro-level parameters (Krishnamurthy and Kriström, 2015; Fell et al., 2014; Alberini et al., 2011; Reiss and White, 2005) and avoid aggregated biases (Fell et al., 2014; Bohi, 1982).

Residential electricity consumption in Taiwan was approximately 47.6 billion kilowatt hour (kW h) in 2017, which is 18% of total electricity consumption, based on the BOE. The histogram of annual electricity consumption per household between 2014 and 2017 was drawn in Fig. 2 according to the survey data of this study. The distribution was right-skewed, which was supported by the positive skewness (SK = 1.86 > 0).[3] The right-skewness can also be observed in Fig. 2, compared to the curve of normal distribution. The skewed sample will cause estimated results biased when the ordinary least squared (OLS) regression is used (Coxe et al., 2009). To fix this problem, appropriate right-skewed regression models were employed in this study.

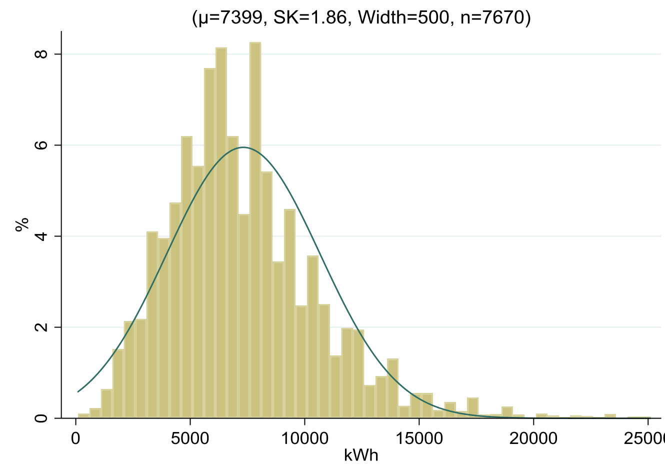

Fig. 2. Annual residential electricity consumption in Taiwan (2014–2017).

Electricity is demanded for appliances that provide services to the household. Electricity consumption depended heavily on ownership of energy intensive appliances (Brounen et al., 2012; Reiss and White, 2005). The percentages of electricity consumption of appliances from 2014 to 2017 in the residential sector were shown in Fig. 3, based on the survey data of this study. Air conditioner (AC) was the highest electricity-consuming appliance, which consumed 35.74% of total electricity. Following were lighting (20.45%), television (TV; 8.75%), and refrigerator (6.98%). The histogram of these appliances were shown in Fig. 4. The right-skewed distribution can also be observed, and all of the skewness were positive.

The appliance-specific models reveal more information related to the household electricity consumption behavior. However, there is a little research discussing this topic due to the limitation of data collection (Kelly and Knottenbelt, 2015; Fang et al., 2012; Depuru et al., 2011). The right-skewed regression models were also rarely discussed in previous research. The household electricity consumption was estimated based on a questionnaire survey in this study. Appliance-specific models were also built to address the right-skewed distributed electricity consumption of AC, lighting, TV, and refrigerator in the micro level. Constructing models provides more information to discover key factors affecting electricity consumption, which can assist government in policy formulation.

2.2. Label for energy efficiency appliances

The voluntary Energy Efficiency Label Program is executed by the BOE in Taiwan since 2001. Appliances with this endorsement label is recognized by the government that its energy efficiency is ranked at top 30% compared to the similar products in the market. This energy efficient is 10–50% higher than Taiwan's National Standards. The efficiency criteria are then periodically reviewed and revised to reflect technology advancement and ensure the credibility. EE label covered 51 product categories. By September 2018, 7365 products, which belong to 326 brands, were available for purchase consideration.[4]

[3] Skewness (SK) is a measure of the asymmetry of the probability distribution of a real-valued random variable. The skewness value can be positive (right-skewness) or negative (left-skewness), or 0 (Groeneveld and Meeden, 1984).

[4] According to the official website of EE label in Taiwan (www.energylabel.org.tw/englishlabel).

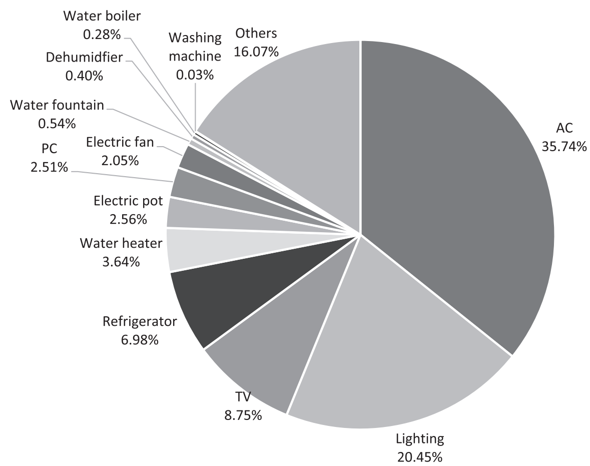

Fig. 3. Residential electricity consumption by appliances (2014–2017).

Star in the U.S. (Brown et al., 2002; Ward et al., 2011), the Group for Energy Efficiency Appliances (GEEA) Label in Europe (Proto et al., 2007), and the Energy Label in Japan, EE label in Taiwan reveals the information of energy efficiency which assist consumers in choosing new appliances (Mahlia and Saidur, 2010).

The average number of appliance with and without EE label per household between 2014 and 2017 was shown in Fig. 5, according to the survey data in this study. Approximately half of appliances had EE label in the residential sector. Averagely, a household had 2.8 ACs, including 1.5 with EE label, so the percentage of EE labeled AC was 53.7%. This percentage was 47.3% for TV and 57.4% for refrigerator. Moreover, a representative household had 23.9 light bulbs/tubes and 42.3% of them were high energy efficient products. The number of lighting products were skipped in Fig. 5 due to its relatively large scale.

2.3. Rebound effects

Giving the consumption behavior constant, energy consumption

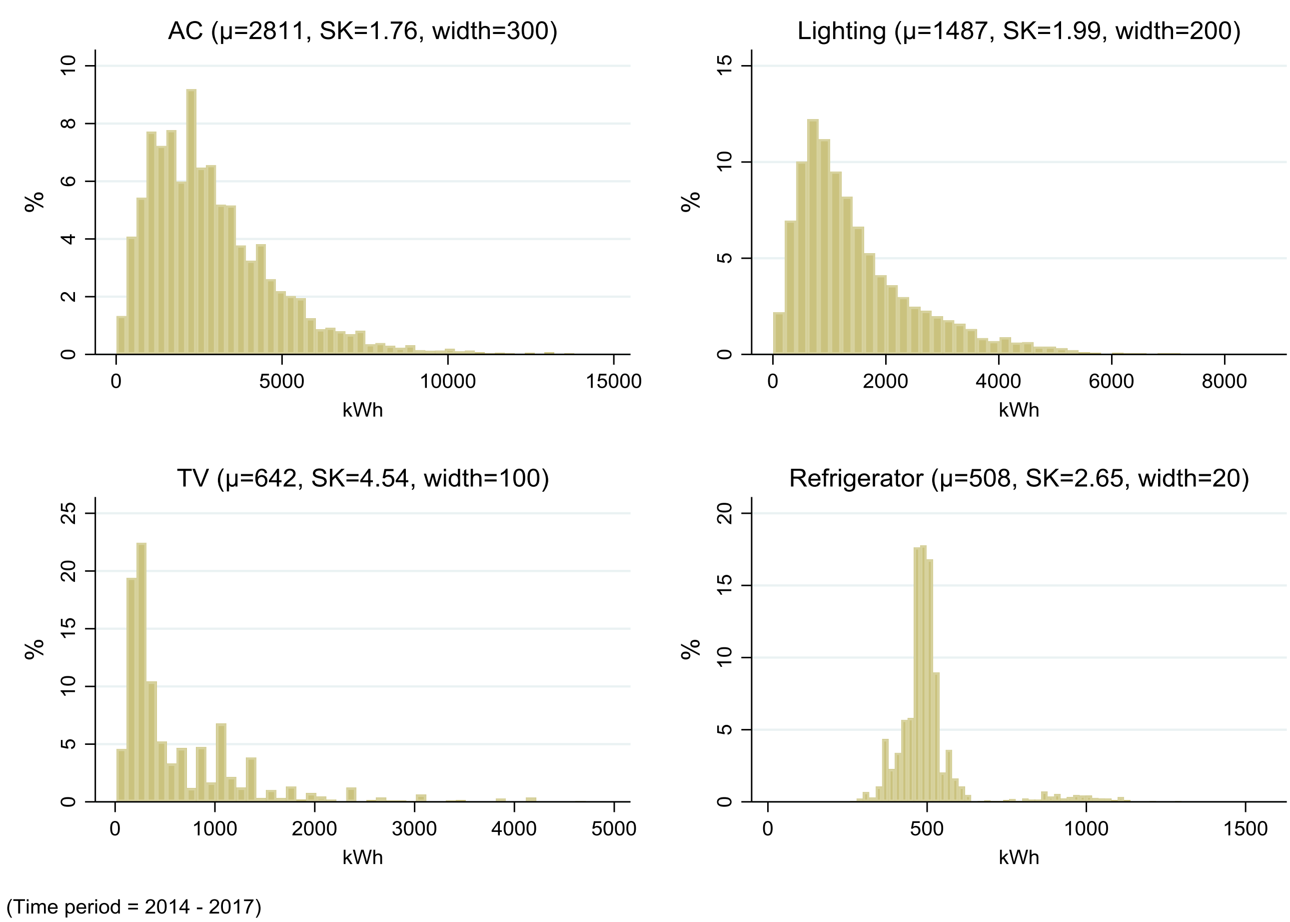

Fig. 4. Annual residential electricity consumption by appliances.

Applications with EE label were officially recognized as higher energy efficiency. In other words, they are expected to save energy giving the consumption behavior constant. The expected electricity saving was 378.01 kW h per AC, 120.26 kW h per TV, 133.63 kW h per refrigerator, and 23.15 kW h per light bulb/tube, based on the BOE.[5] Like the Energy decreases when households use appliances with EE label. This expected energy saving is the *direct effect* of energy efficiency improvement. However, consumers tend to consume more energy due to economic benefit from efficiency improvement (Berkhout et al., 2000), causing actual energy saving smaller than expected one. This additional energy consumption due to efficiency improvement is the *rebound effect*, and defined as

[5] These numbers were obtained from arithmetically averaging the official electricity saving of all labeled products within each product category in 2017, based on the BOE. Expected electricity saving of lighting was additionally calculated from the difference of electricity consumption between representative high efficient and general lighting products, weighted on market shares. High electricity efficient lights were defined as T5 fluorescent light tubes and LED light bulbs/tubes.

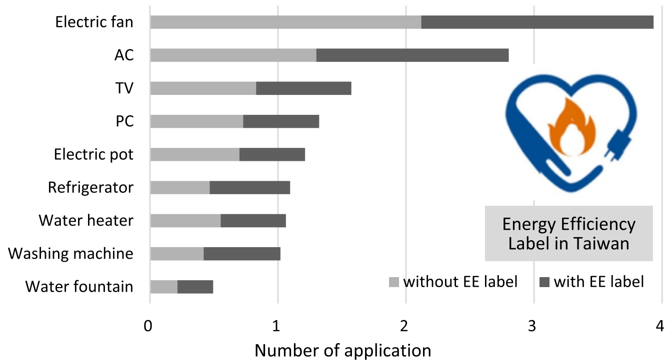

Fig. 5. Numbers of appliances per household (2014–2017).

$$\text{Rebound effect} = \frac{\textit{Expected energy saving} - \textit{Actual energy saving}}{\textit{Expected energy saving}} \times 100\%. \tag{1}$$

Partial energy is still saved when rebound effect is smaller than direct effect. If rebound effect is larger than direct effect, however, more energy is consumed due to efficiency improvement, and this is so-called *backfire effect* (Berkhout et al., 2000).

Two approaches are often employed to calculate rebound effect. First is the macro approach, which used aggregated data to study the effect of technical progress on energy consumption and were often driven by the elasticity of price (Li and Han, 2012; Lin and Liu, 2012; Freire-González, 2011; Allan et al., 2007; Berkhout et al., 2000; Laitner, 2000; Saunders, 2000). Second is the micro approach. With survey data, the rebound effect of cooling and heating system (Nesbakken, 2001; Jin, 2007; Haas and Biermayr, 2000), lighting (Roy, 2000), washing machine (Davis, 2008), and vehicle (Frondel et al., 2008; Hymel et al., 2010) were investigated.

In previous research, the size of rebound effect is different among regions and products. Some research found that rebound effect was tiny and can be ignored (Davis, 2008; Berkhout et al., 2000; Greening et al., 2000; Laitner, 2000; Saunders, 2000). Some studies concluded that rebound effect is large and significantly affected the achievement of energy efficiency improvement (Li and Han, 2012; Freire-González, 2011; Allan et al., 2007; Jin, 2007; Nesbakken, 2001; Haas and Biermayr, 2000; Roy, 2000). However, there was little research addressing to Taiwan. In this paper, Taiwan's appliance-specific rebound effect in the micro level was studied. This results are important in evaluating the actual influence of energy efficiency measures.

3. Poisson and negative binomial regression model

The right-skewed distributions in common use are Poisson and negative binomial distribution. These two distributions were especially used for count data (Long and Freese, 2006). Electricity consumption, which is non-negative integer based on the bimonthly electricity bill, fits the data characteristics. The Poisson regression model (PRM) assumes that the dependent variable y, annual electricity consumption, is drawn from a Poisson distribution with mean μ, where μ is estimated from the independent variables $\mathbf{x}$ in the model. This model can be expressed as

$$\mu = E(y \mid \mathbf{x}) = exp(\mathbf{x}\boldsymbol{\beta}) \tag{2}$$

where $\boldsymbol{\beta}$ is the parameter vector. Taking the exponential forces μ to be positive, which is necessary because electricity consumption is positive. Meanwhile, the Poisson distribution is

$$P(y \mid \mu) = \frac{e^{-\mu}\mu^{y}}{y!}. \tag{3}$$

For a Poisson distribution, the mean μ is also the variance, i.e. $Var(y) = \mu$. However, a variance is often greater than the mean in real data, which is called ***overdispersion***. The negative binomial regression model (NBRM) addresses this failure of the PRM by adding the parameter α, and the distribution is expressed as

$$P(y \mid \mu) = \frac{\Gamma(y+\alpha^{-1})}{y!\Gamma(\alpha^{-1})}\left(\frac{\alpha^{-1}}{\alpha^{-1}+\mu}\right)^{\alpha^{-1}}\left(\frac{\mu}{\alpha^{-1}+\mu}\right)^{y} \tag{4}$$

where $\Gamma(.)$ is a gamma function. The NBRM reduces to the PRM when $\alpha = 0$. In other words, overdispersion can be tested by a likelihood-ratio (LR) test of H_0: $\alpha = 0$. Using this test, accurate models can be chosen.

Marginal effects were then calculated after obtaining accurate models and parameters. Marginal effect indicates the change of $E(y|\mathbf{x})$ for a given change in one independent variable x_k, holding all other variables constant. For nonlinear models such as PRM and NBRM, marginal effect has more economic meanings than parameter β itself. For a continuous variable, the marginal effect of x_k on y is defined as

$$\frac{\partial E(y \mid \mathbf{x})}{\partial x_k} = E(y \mid \mathbf{x})\beta_k. \tag{5}$$

For a dummy variable, the marginal effect is computed by letting x_k change from 0 to 1 and expressed as

$$\frac{\Delta E(y \mid \mathbf{x})}{\Delta x_k(0 \to 1)} = E(y \mid \mathbf{x},\ \ x_k = 1) - E(y \mid \mathbf{x},\ \ x_k = 0). \tag{6}$$

Additional details of PRM and NBRM were provided by Long and Freese (2006) and Gardner et al. (1995).

4. Data

4.1. Questionnaire survey

Data for the analysis were drawn from a project of BOE in Taiwan, as part of annual questionnaire survey on household energy consumption behavior from 2012 to 2017. The time span of data in this study was between 2014 and 2017 because the questionnaire had a major revise in 2014. Four-year pooled data, instead of one-year cross sectional data, were used to increase sample size, and to identify the time trend of electricity consumption from 2014 to 2017. Approximately 2000 households in every year were surveyed using interview questionnaire. Sample selection followed a strategy of stratification based on region and household income. Excluding the invalid questionnaires, the total sample size of this study was 7677; in other words, the dropout rate was nearly 4%. The questionnaire consisted of nearly 300 questions, with an average completion time of nearly 40 min. The survey was administrated in traditional Chinese.

The survey collected information regarding house type, energy expenditure, physics power/size of appliances, appliance-specific usage hours per day in summer and non-summer month,[6] EE labeled appliances, and household socioeconomic characteristics. Households were requested to provide electricity consumption data based on their bimonthly electric bill in Taiwan Dollar (TWD) or kW h to double check the correctness of answers.

Questions regarding the EE label were asked by a two-step process. First was whether households know their appliances have EE label. If the answer was yes, how many appliances have EE label (including zero) was further checked. This process was conducted to filter the samples who are uncertain about the condition of their appliances. In other words, the change of consumption behavior due to rebound effect can be identified only when consumers know the fact that the energy efficiency of their appliances has been improved. However, the sample size shrunk in exchange for data reliability.

[6] Summer months are June, July, August, and September based on TaiPower Company.

Table 1
Descriptive statistics.

Variable	Description		Unit	Obs	Mean	SD	Min	Max
Dependent variables								
ELECTRICITY	Residential electricity consumption		kW h	7670	7399	3625	97	45,136
AC	Residential electricity consumption of *AC*		kW h	7677	2811	2088	0	20,427
LIGHT	Residential electricity consumption of *lighting*		kW h	7677	1487	1146	0	14,664
TV	Residential electricity consumption of *TV*		kW h	7676	642	801	0	12,897
REFRIGERATOR	Residential electricity consumption of *refrigerator*		kW h	7677	508	134	0	1566
Independent variables								
INCOME	Household annual income		10,000 TWD	7655	87.252	40.025	10	400
AREA	Indoor floor area of the house		Ping	7675	41.733	19.225	4	200
HOUSEAGE	Age of house		Year	7673	23.317	10.515	5	45
HOUSETYPE1	House type: bungalow	(*dummy*, base: apartment)	–	7677	0.072	0.258	0	1
HOUSETYPE2	House type: house	(*dummy*, base: apartment)	–	7677	0.425	0.494	0	1
OWN	Ownership of house	(*dummy*, base: rent a house)	–	7677	0.897	0.305	0	1
AGE0–4	Number of household member with *age 0–4*		People	7675	0.094	0.329	0	2
AGE5–19	Number of household member with *age 5–19*		People	7675	0.913	0.927	0	5
AGE20–34	Number of household member with *age 20–34*		People	7675	0.688	0.933	0	6
AGE35–64	Number of household member with *age 35–64*		People	7673	1.831	0.817	0	7
AGE65UP	Number of household member with *age 65 up*		People	7676	0.443	0.716	0	5
CENTRAL	Region: central Taiwan	(*dummy*, base: northern Taiwan)	–	7677	0.243	0.429	0	1
SOUTH	Region: southern Taiwan	(*dummy*, base: northern Taiwan)	–	7677	0.231	0.421	0	1
EAST	Region: eastern Taiwan	(*dummy*, base: northern Taiwan)	–	7677	0.053	0.224	0	1
Y2014	Year 2014	(*dummy*, base year: 2017)	–	7677	0.307	0.461	0	1
Y2015	Year 2015	(*dummy*, base year: 2017)	–	7677	0.251	0.434	0	1
Y2016	Year 2016	(*dummy*, base year: 2017)	–	7677	0.184	0.388	0	1
Energy efficiency (EE) label								
ACEEL	Number of *AC* with EE label		Number	806	1.831	1.588	0	6
ACnoEEL	Number of *AC* without EE label		Number	806	1.584	1.468	0	6
LIGHTEEL	Number of *light bulb/tube* with EE label		Number	535	10.501	11.171	0	46
LIGHTnoEEL	Number of *light bulb/tube* without EE label		Number	535	14.538	11.794	0	60
TVEEL	Number of *TV* with EE label		Number	197	0.893	0.724	0	4
TVnoEEL	Number of *TV* without EE label		Number	197	1.548	0.883	0	6
RFEEL	Number of *refrigerator* with EE label		Number	2698	0.709	0.510	0	5
RFnoEEL	Number of *refrigerator* without EE label		Number	2698	0.388	0.560	0	5

Note: 1. In 2017, one USD = 30.439 TWD. 2. Ping is a common unit of floor area in Taiwan, and one Ping = 3.3058 m^2.

4.2. Variables

Thirty variables out of the questionnaire survey were employed in this study. The descriptive statistics were listed in Table 1. The dependent variable was ***electricity consumption*** (*ELECTRICITY*). For household models, most electricity consumption was obtained directly from the survey, but a small part of sample was converted from electric bill in TWD to kW h by the average nominal residential electricity price (2.57 TWD/kW h), based on the TaiPower Company. For appliance models, the appliance-specific electricity consumption was additionally calculated from the physics power (W) and usage hours of the appliance. Appliances covered AC, lighting, TV, and refrigerator. These four appliances covered 72% of residential electricity consumption in Taiwan (see Fig. 3).

Independent variables considered the house characteristics and socioeconomic conditions of households. ***Household annual income*** (*INCOME*) was used to analyze the income effect on electricity demand. Households with higher income tend to consume more electricity because electricity is normal goods (Su, 2018; Yoo et al., 2007; Reiss and White, 2005; Filippini and Pachauri, 2004). Thus, the expected influence of income was positive.

The ***floor area*** (*AREA*) measures the indoor floor area of house. Larger houses consume more electricity. Larger space needs higher cooling or heating capability of air conditioner (Abrahamse and Steg, 2009; Holloway and Bunker, 2006) or more lighting. The expected influence of floor area on electricity consumption was thus positive. The ***age of house*** (*HOUSEAGE*) measures how old the house is. Newer house had more modern appliances so the electricity consumption increased (Holloway and Bunker, 2006). Comparatively, old houses with aging electrical system provides limited power supply, especially for those older than 20 years. Households living in old houses may consume less electricity based on the appliance and voltage constrain. Thus the expected effect of house age was negative.

Three ***types of house*** were considered through dummy variables. Apartments are the most common house type (50%) in Taiwan, which were used as a based variable. Bungalows (*HOUSETYPE1*) and ordinary houses (*HOUSETYPE2*; including detached house, semi-detached house, and terrace house) were controlled. Another dummy variable controlled the ***ownership of house*** (*OWN*). Compared to renting a house, owning a house represents the household has settled down and has less probability to move. In Taiwan's society, most people tend to buy a house if they can afford, and renting a house is usually a period of transition. When households own their house, more appliances are bought to have a more comfortable living environment and consume more electricity. Thus, the expected effect of owning a house was positive.

Considering the electricity consumption behavior was different among residents' ages, this study controlled the number of household members with five ***age groups***: infancy (*AGE0–4*), child and adolescence (*AGE5–19*), early adulthood (*AGE20–34*), midlife (*AGE35–64*), and elder (*AGE65UP*). It is expected that households with infant tend to consume more electricity to maintain a comfortable temperature and humidity. Households with senior citizen may consume less electricity because elders own less energy-intensive appliances and tend to save money (Brounen et al., 2012).

Dummy variables were also employed to control ***regions*** and ***years***. Four regions include northern, central (*CENTRAL*), southern (*SOUTH*), and eastern (*EAST*) Taiwan. Regional dummies controlled not only climate difference but also local consuming behavior. Time span was from 2014 to 2017 so three dummies (*Y2014*, *Y2015*, and *Y2016*) with base year 2017 were used. Note that the price effect was included in the

Table 2
Correlation coefficients.

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
INCOME	1	1.000															
AREA	2	0.100	1.000														
HOUSEAGE	3	− 0.108	− 0.019	1.000													
HOUSETYPE1#	4	− 0.191	− 0.113	0.194	1.000												
HOUSETYPE2#	5	− 0.046	0.565	0.081	− 0.238	1.000											
OWN#	6	0.120	0.137	− 0.012	− 0.069	0.123	1.000										
AGE0–4	7	0.025	− 0.013	− 0.038	0.012	− 0.025	0.017	1.000									
AGE5–19	8	0.120	0.077	− 0.098	− 0.110	0.018	0.063	− 0.139	1.000								
AGE20–34	9	0.178	0.091	− 0.012	− 0.044	0.036	− 0.028	0.070	− 0.474	1.000							
AGE35–64	10	0.310	0.147	− 0.034	− 0.114	0.100	0.156	− 0.027	0.284	− 0.257	1.000						
AGE65UP	11	0.010	0.157	0.092	0.083	0.139	0.080	− 0.009	− 0.027	− 0.099	− 0.124	1.000					
CENTRAL#	12	− 0.277	0.206	0.030	0.169	0.177	− 0.055	− 0.073	− 0.089	− 0.009	− 0.081	0.032	1.000				
SOUTH#	13	− 0.131	0.106	− 0.019	− 0.091	0.198	− 0.020	0.005	− 0.087	0.045	− 0.051	− 0.030	− 0.309	1.000			
EAST#	14	0.022	0.031	0.045	0.071	0.116	0.023	− 0.028	0.020	− 0.056	0.045	0.109	− 0.133	− 0.129	1.000		
Y2014#	15	0.029	0.027	− 0.030	0.007	0.019	0.010	− 0.013	0.052	0.024	0.035	− 0.069	0.005	− 0.002	− 0.012	1.000	
Y2015#	16	− 0.033	− 0.027	− 0.016	0.008	− 0.013	− 0.016	0.015	0.037	− 0.054	− 0.001	0.037	0.003	− 0.005	− 0.010	− 0.386	1.000
Y2016#	17	0.029	− 0.004	− 0.016	0.009	− 0.004	− 0.056	0.011	− 0.014	0.001	− 0.045	0.041	− 0.014	0.008	0.025	− 0.316	− 0.275

Note: # stands for dummy variable.

year dummies. Taiwan's electricity prices are reviewed and adjusted every year, which were proposed by the TaiPower Company and approved by the Ministry of Economic Affairs of Taiwan.

Number of appliances with and without EE label were employed to analyze the rebound effect of energy efficient appliances. Targeted appliances covered AC, lighting, TV, and refrigerator. It is expected that appliances with EE label (*ACEEL*, *LIGHTEEL*, *TVEEL*, and *RFEEL*) consume less electricity than that without EE label (*ACnoEEL*, *LIGHTnoEEL*, *TVnoEEL*, and *RFnoEEL*). The difference of electricity consumption between appliances with and without EE label was the actual saving due to efficiency improvement. Comparing this actual saving to the expected saving based on the BOE, the appliance-specific rebound effects can be obtained.

The correlation coefficients were listed in Table 2. There is no high correlation between any two explanatory variables.

5. Estimated results

5.1. Household models

The estimated results of household electricity demand were listed in Table 3. Model 1 is the estimated results using pooled OLS regression. This model assuming normal distribution was just for reference because household electricity consumption is a right-skewed distribution. The PRM (Model 2) and NBRM (Model 3) were thus estimated. After testing the significance of α parameter, NBRM is more accurate than PRM due to the overdispersion of data. The predicted annual electricity consumption per household was 7175 kW h based on Model 3. The difference of predicted y between Model 1 and 3 also indicates that the pooled OLS regression model overestimated the expected value of electricity consumption due to the incorrect assumption of distribution.

Marginal effects of Model 3, based on Eqs. (5) and (6), were listed in Table 3. Increasing household annual income by 10,000 TWD will rise the electricity consumption by 9.59 kW h. This positive income effect indicates that electricity is normal goods. Considering the difference of household annual incomes between highest and lowest 20% was 1.71 million TWD in Taiwan in 2017, the difference of electricity consumption between these rich and poor households was nearly 1644 kW h. When indoor floor area increases by one Ping (i.e. 3.3 m^2), additional 32.46 kW h of electricity will be consumed. Estimated results also indicated that older house consumes less electricity. Compared to apartments, bungalows consume less electricity (623.99 kW h), but there is no significant difference of electricity consumption between ordinary houses and apartments. If households own their houses, more electricity (339.75 kW h) will be used.

Increase household members will rise electricity consumption, but this effect is different among age groups. As the main breadwinners in a household, people in their midlife consume the most electricity (757.14 kW h per person) compared to other age groups. Following is people in their early adulthood, who consume 713.9 kW h per person. Adults consume more electricity, probably due to the fact that they can afford and own a lot of energy intensive appliances. Households with infant, who are more sensitive to the house environment, consume more electricity (676.62 kW h per person) than households with child and adolescence (556.9 kW h per person). Senior citizens, as expected, consume the least electricity (539.36 kW h per person).

Regional and yearly effects were also statistically significant. Northern Taiwan consumed more electricity than other three regions, while central Taiwan consumed the least. Electricity consumption in 2016 and 2017 reduced substantially.

5.2. Appliance models

Estimated results of appliance-specific models were listed in Table 4. Dependent variables were electricity consumption from AC, lighting, TV, and refrigerator in Model 4–7 respectively. According to

Table 3
Estimated results of household electricity demand.

	Model 1		Model 2		Model 3			
	Pooled OLS		**PRM**		**NBRM**		**NBRM-ME**	
INCOME	9.34	***	0.0011	***	0.0013	***	9.59	***
	(1.65)		(0.0002)		(0.0002)		(1.38)	
AREA	35.68	***	0.0043	***	0.0045	***	32.46	***
	(3.75)		(0.0004)		(0.0004)		(2.92)	
HOUSEAGE	− 22.86	***	− 0.0035	***	− 0.0039	***	− 28.09	***
	(3.85)		(0.0005)		(0.0005)		(3.85)	
HOUSETYPE1#	− 317.24	**	− 0.0702	***	− 0.0904	***	− 623.99	***
	(145.52)		(0.0235)		(0.0234)		(155.16)	
HOUSETYPE2#	− 117.79		− 0.0103		− 0.0145		− 104.05	
	(114.18)		(0.0150)		(0.0147)		(105.45)	
OWN#	277.12	**	0.0522	***	0.0483	**	339.75	**
	(127.58)		(0.0198)		(0.0196)		(135.02)	
AGE0–4	618.39	***	0.0849	***	0.0943	***	676.62	***
	(125.41)		(0.0156)		(0.0152)		(109.15)	
AGE5–19	487.12	***	0.0722	***	0.0776	***	556.90	***
	(59.03)		(0.0079)		(0.0076)		(54.23)	
AGE20–34	660.49	***	0.0926	***	0.0995	***	713.90	***
	(67.33)		(0.0085)		(0.0081)		(58.02)	
AGE35–64	681.03	***	0.0945	***	0.1055	***	757.14	***
	(62.37)		(0.0080)		(0.0080)		(57.33)	
AGE65UP	619.41	***	0.0757	***	0.0752	***	539.36	***
	(61.88)		(0.0075)		(0.0073)		(52.18)	
CENTRAL#	− 1287.89	***	− 0.1889	***	− 0.1879	***	− 1285.92	***
	(116.20)		(0.0164)		(0.0158)		(101.79)	
SOUTH#	− 818.87	***	− 0.1133	***	− 0.1184	***	− 823.65	***
	(110.93)		(0.0151)		(0.0149)		(99.25)	
EAST#	− 1025.42	***	0.0256	***	− 0.1432	***	− 964.64	***
	(182.07)		(0.0256)		(0.0237)		(149.61)	
Y2014#	1511.54	***	0.2040	***	0.2013	***	1504.39	***
	(98.94)		(0.0133)		(0.0137)		(108.12)	
Y2015#	1513.50	***	0.2075	***	0.2117	***	1604.42	***
	(93.74)		(0.0129)		(0.0133)		(107.12)	
Y2016#	− 82.77		− 0.0118		− 0.0057		− 40.49	
	(90.60)		(0.0140)		(0.0141)		(100.88)	
Constant	2700.82	***	8.2660	***	8.2254	***		
	(227.75)		(0.0315)		(0.0308)			
Alpha					0.1651	***		
					(0.0038)			
R^2	0.2387							
Wald chi^2			2245.87	***	2248.49	***		
Pseudo R^2			0.2619		0.0168			
Obs.	7636		7636		7636			
Predicted y	7398.52						7174.96	

Note: 1. Standard deviations are in parentheses. 2. *, ** and *** denote significance at the 10%, 5% and 1% statistical levels. 3. # stands for dummy variable. 4. ME stands for marginal effect.

the test results of the significance of α parameter, NBRM is more accurate than PRM for these four models. A representative household in Taiwan annually consumed 2625 kW h for AC, 1432 kW h for lighting, 593 kW h for TV, and 505 kW h for refrigerator.

The marginal effects of income were all significantly positive. Increasing household annual income by 10,000 TWD will rise the electricity consumption by 4.22 kW h for AC, 2.34 kW h for lighting, 0.45 kW h for TV, and 0.27 kW h for refrigerator. The indoor floor area of house also had positive effect on household electricity consumption, especially for AC and lighting. For additional one Ping of floor area, electricity consumption will increase by 22.25 kW h for AC, 12.09 kW h for lighting, 3.09 kW h for TV, and 1.21 kW h for refrigerator. Old houses often have limited electricity supply, so the electricity use of AC and TV in old houses decreased. Bungalows consumed least electricity from AC, lighting, and refrigerator, but most electricity form TV, compared to ordinary house and apartment. Apartments consumed most electricity from AC, but least electricity from TV. Owning a house will increase electricity consumption. When a household owns their house, electricity consumption will averagely rise by 156.29 kW h for AC, 198.72 kW h for lighting, 64.37 kW h for TV, and 11.24 kW h for refrigerator. The relatively high value of lighting may indicate the potential problem of over illumination when people design their new houses.

Table 4
Estimated results of appliance electricity consumption (marginal effects).

	Model 4 AC		Model 5 Lighting		Model 6 TV		Model 7 Refrigerator	
INCOME	4.22	***	2.34	***	0.45	*	0.27	***
	(0.73)		(0.38)		(0.23)		(0.04)	
AREA	22.25	***	12.09	***	3.09	***	1.21	***
	(1.58)		(0.82)		(0.54)		(0.12)	
HOUSEAGE	− 20.77	***	1.11		− 3.61	***	0.10	
	(2.21)		(1.16)		(0.77)		(0.13)	
HOUSETYPE1#	− 792.25	***	− 76.55	*	148.77	***	− 18.71	***
	(84.08)		(46.28)		(38.52)		(5.93)	
HOUSETYPE2#	− 191.66	***	19.88		108.63	***	0.26	
	(57.34)		(32.02)		(19.86)		(3.75)	
OWN#	156.29	**	198.72	***	64.37	***	11.24	***
	(78.03)		(36.46)		(23.94)		(4.31)	
AGE0–4	421.35	***	157.31	***	128.02	***	12.57	***
	(64.04)		(33.92)		(23.56)		(3.68)	
AGE5–19	416.80	***	116.51	***	61.19	***	13.91	***
	(28.49)		(15.19)		(9.42)		(1.90)	
AGE20–34	416.09	***	16.46		94.43	***	9.33	***
	(31.77)		(17.00)		(10.36)		(2.01)	
AGE35–64	499.53	***	67.35	***	155.86	***	13.95	***
	(33.80)		(16.84)		(10.74)		(2.11)	
AGE65UP	255.79	***	8.53		128.35	***	19.73	***
	(32.38)		(18.25)		(11.20)		(2.22)	
CENTRAL#	− 787.01	***	− 297.15	***	− 128.15	***	64.99	***
	(53.96)		(31.12)		(19.31)		(4.92)	
SOUTH#	− 72.05		− 329.93	***	− 83.07	***	14.56	***
	(58.63)		(28.53)		(18.77)		(3.55)	
EAST#	− 646.56	***	− 658.28	***	− 227.29	***	15.69	***
	(67.72)		(30.12)		(21.43)		(5.94)	
Y2014#	− 143.03	**	− 122.35	***	− 39.01	**	− 32.70	***
	(56.01)		(30.41)		(19.10)		(3.53)	
Y2015#	− 229.43	***	− 91.21	***	− 55.05	***	0.94	
	(54.62)		(32.35)		(19.21)		(3.54)	
Y2016#	− 398.76	***	− 139.86	***	− 57.06	***	− 2.46	
	(56.72)		(32.66)		(20.01)		(4.11)	
Alpha	0.7998	***	0.4666	***	0.8194	***	0.0524	***
	(0.0269)		(0.0091)		(0.0158)		(0.0037)	
Wald chi^2	1555.33	***	1214.65	***	983.10	***	919.63	***
Pseudo R^2	0.0090		0.0092		0.0119		0.0134	
Obs.	7643		7643		7643		7643	
Predicted y	2624.78		1431.60		593.10		505.04	

Note: 1. Standard deviations are in parentheses. 2. *, ** and *** denote significance at the 10%, 5% and 1% statistical levels. 3. # stands for dummy variable.

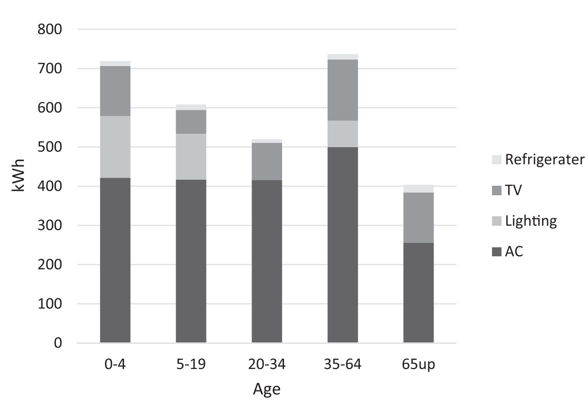

Fig. 6. Effects of age groups on appliance electricity consumption.

The marginal effects of age groups on appliance-specific electricity demand were shown in Fig. 6. For all age, most electricity was used from AC, especially for those with age between 35 and 64. However, compared to other age groups, senior citizens consumed least electricity of AC. Households with infants demand the highest electricity in lighting. Household members in their midlife and older used more electricity in watching TV. Children, adolescence, and young adults used less electricity in watching TV. The effects of age groups indicate that policies addressing specific age groups should be designed individually based on the electricity consumption behavior. For advocating the increase of air conditioner temperature by 1 °C, for example, the targeted group is people in midlife. For promoting the habit of turning lights off when leaving a room, household with infant and children should be addressed.

Table 5
Marginal effects of appliances with and without EE labels on electricity consumption.

	Model 8 *AC*		Model 9 *AC*		Model 10 *Lighting*		Model 11 *Lighting*		Model 12 *TV*		Model 13 *TV*		Model 14 *Refrigerator*		Model 15 *Refrigerator*	
Without EE label	181.75 (48.56)	***			34.77 (3.34)	***			205.67 (25.85)	***			71.98 (5.27)	***		
With EE label			76.40 (47.85)	***			14.21 (3.70)	***			89.24 (38.80)	***			31.73 (5.80)	***
Control var.	Yes		Yes		Yes		Yes		Yes		Yes		Yes		Yes	
Wald chi^2	224.14	***	190.70	***	360.66	***	229.73	***	394.02	***	212.98	***	738.97	***	518.66	***
Pseudo R^2	0.0114		0.0106		0.0281		0.0173		0.0605		0.0462		0.0322		0.0230	
Obs.	800		800		532		532		196		196		2686		2686	
Predicted y	2619.86		2628.41		1431.70		1468.17		552.26		568.77		527.30		528.54	
Equality test			**43.71**	***			**95.15**	***			**34.96**	***			**266.12**	***

Note: 1. Standard deviations are in parentheses. 2. *** denotes significance at the 1% statistical level. 3. Equality test tests the significance of difference of marginal effects between appliances with and without EE label.

5.3. Appliance-specific rebound effect

The number of appliances with and without EE label were added separately into models to study the electricity saving of EE label. Subsample was used after filtering out observations who not know whether their appliance has EE label. The NBRM was chosen based on the testing results. Estimated results were listed in Table 5. Model 8, 10, 12, and 14 were models for appliances without EE labels; while Model 9, 11, 13, and 15 were models for appliances with EE labels. Due to the negative correlation between the number of appliance with and without EE labels, estimation was separated to avoid the multicollinearity.[7] The controlled variables in Model 8–15 were set as same as Model 3. In addition, to replace energy inefficient appliances in the residential sector, Taiwan government subsidized high EE appliances to consumers in 2012, 2013, and 2015, based on the BOE. The nationwide policy induced many households with different socioeconomic background to replace their appliances. The extensive replacement created sufficient observations with EE-labeled appliances. It also causes the relationship between the numbers of EE labeled appliance and other explanatory variables uncorrelated (Lenzen et al., 2006; Abrahamse and Steg, 2009).

Appliances with EE label consumed less electricity than that without EE label. The equality test is employed to test whether the marginal effects between appliances with and without EE label on electricity consumption were different. Tested results in Table 5 indicated that all the differences were statistically significant. This difference of marginal effects is thus household's actual electricity saving due to using high energy efficient appliances. A household using appliances with EE label can annually save 105.35 kW h per AC, 20.55 kW h per light bulb/tube, 116.43 kW h per TV, and 40.25 kW h per refrigerator, compared to those without EE label. Note that the predicted y in Table 5 was alike between same appliances with and without EE labels. This fact indicates that the actual electricity saving due to efficiency improvement can not be obtained without controlling other variables.

Comparing the actual electricity saving to the expected saving, the appliance specific rebound effects were calculated in Table 6, based on Eq. (1). The rebound effect in Taiwan was 72% for AC, 11% for lighting, 3% for TV, and 70% for refrigerator. The rebound effect was large for AC and refrigerator. Compared to other countries, Taiwan's rebound effect of AC is quite close to Korea (Jin, 2007), but larger than Norway (Nesbakken, 2001) and Austria (Haas and Biermayr, 2000). For lighting, Taiwan's rebound effect is much smaller than India (Roy, 2000). Due to the economic benefit from efficiency improvement, households tend to change their consumption behavior and thus consume more electricity, such as extending the use time of AC, lowering the temperature of AC, or choosing a larger refrigerator to replace the old one. Thus, the expected electricity saving of AC and refrigerator with EE label was partially offset by the changes of electricity consumption behavior. On the contrary, the rebound effect was small for lighting and TV. The consuming patterns were rarely changed so that these appliances with EE label can actually save electricity. Due to rebound effects, the residential electricity saving from EE improvement needs to be discounted when evaluating policy effects.

Table 6
Rebound effects.

	Electricity saving		Rebound effect
	Actual (kW h)	Expected (kW h)	(%)
AC	105.35	378.01	**72**
Light bulb/tube	20.55	23.15	**11**
TV	116.43	120.26	**3**
Refrigerator	40.25	133.63	**70**

The overall rebound effect, weighted on electricity consumption, was at least 33% in Taiwan's residential sector.[8] This effect is quite similar to that in Spain (Freire-González, 2011) and Korea (Jin, 2007), but larger than that in Netherlands (Berkhout et al., 2000) and the United States (Laitner, 2000). Households consider not only minimizing electricity costs but also increasing life quality. Life quality is more and more important after Taiwan became a high-income economy in 1987 according to the World Bank. Thus, improving EE of appliances induces additional electricity consumption behavior, causing residential electricity consumption grew faster than aggregated one. Note that the rebound effect estimated in this paper was limited to the difference of electricity consumption between households with old appliances and that with EE-labeled appliances. The general rebound effect, which is driven by the elasticity of price, is not discussed in this study due to data characteristics. This study estimated possible negative effect when governments introduce EE programs in the future.

[7] The correlation coefficients between appliances with and without EE label were − 0.8071 for AC, − 0.5797 for lighting, − 0.6423 for TV, and − 0.8039 for refrigerator. This negative correlation represents that households who have more appliances with EE label will have less appliances without EE label.

[8] The overall rebound effect was estimated by $\sum_{i=1}^{n} s_i r_i$, where s_i represents the share of electricity consumption for appliance i, and r_i represents the appliance-specific rebound effect. Only AC, lighting, TV, and refrigerator were considered, assuming rebound effects of other appliances were zero.

6. Conclusion

The residential electricity demand in Taiwan was investigated using survey data of 7677 households between 2014 and 2017. The right-skewed PRM and NBRM were employed to fit the distribution of household electricity consumption. This study discovers key determinants which affect the electricity demand in the micro level. Separating this demand into appliances focuses on the appliance-specific electricity consumption behavior and related affecting factors. Appliances covered AC, lighting, TV, and refrigerator. The difference of electricity consumption between appliances with and without EE label was also studied. Compared the actual saving to theoretical one, the appliance-specific rebound effects were obtained.

The estimated results indicate that a representative household in Taiwan consumes 7175 kW h electricity annually, including 2625 kW h for AC, 1432 kW h for lighting, 593 kW h for TV, and 505 kW h for refrigerator. Electricity is normal goods due to the positive income effects. The indoor floor area also has positive effect on household electricity consumption, especially for AC and lighting. In old houses, the electricity use of AC and TV decreased. More electricity will be used if households own their houses. Moreover, increase household members will rise electricity consumption, and this effect differs among age groups and appliances. People in their midlife consume the most electricity, while senior citizens consume the least. The most electricity was used from AC, especially for those with age between 35 and 64. Households with infants and children consume more electricity from lighting. Elder people consume more electricity from watching TV.

Moreover, a representative household using appliances with EE label can actually save 105.35 kW h per AC, 20.55 kW h per light bulb/tube, 116.43 kW h per TV, and 40.25 kW h per refrigerator. The rebound effect in Taiwan is 72% for AC, 11% for lighting, 3% for TV, and 70% for refrigerator. The expected electricity saving of AC and refrigerator with EE label is offset by the changes of electricity-consuming behavior. Thus, the residential electricity saving from EE improvement needs to be discounted when evaluating policy effects.

Further research into the electricity consumption of other appliances, such as water heater or air purifier, will reveal more information in rebound effect and household electricity consumption behavior. This behavior may change gradually to reflect the climate change or technology progress in the future. The pattern of behavior changes can be addressed when the time span of survey data extends. In addition, this research framework can apply to different targets, like transportation sector or iron and steel industry when detailed survey data are collected.

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