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Time Rebound Effect in Households' Energy Use:
Theory and Evidence

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Abstract

Time-saving (time-efficient) goods and services are increasingly developed and diffused. Such goods and services increase the disposable time for households, and the time saved may be allocated to other activities consuming energy/electricity. The present study sets a simple theoretical model and shows a mechanism, called the time rebound effect, with which time-saving goods increase energy consumption through household behaviors. Furthermore, we reveal empirical evidence for this model by conducting a Japanese household survey. In particular, our analysis shows that the time rebound effect occurs on using the dishwasher, clothes dryer, or a net ordering/delivery service. However, its impact is very small: the extra electricity usage is about 1.4% of the daily usage at most.

Keywords: time rebound effect; households; electricity consumption; time allocation; Energy

1. Introduction

In recent years, many new electrical products have been developed and sold to households. For example, "Roomba," an automatic cleaner of the iRobot Corporation, was launched in 2002 in Japan. A decade later, over 8 million Roombas have been sold. Another example is the dishwasher. According to the National Survey of Family Income and Expenditure (2014), the penetration rate of dishwashers was 14.9% in 2004 but increased to 24.7% in 2014. There is also widespread use of clothes dryers that save waiting time for drying clothes. The diffusion of these products obviously contributes to reducing the time spent on housework such as room cleaning, cooking, and washing clothes. Moreover, innovative services as well as these products may reduce housework time. For example, one can now purchase food, everyday items, books, etc., online (through Amazon.com, Rakuten.com, and other online supermarkets). According to the Consumer Confidence Survey (2018), the utilization rate of net ordering/delivery services by Japanese households has increased from only 5.3% in 2002 to 34.2% in 2017. Cooking can also be replaced by ordering online (Uber Eat, Deliveroo and other online delivery services).

The Survey of Time Use and Leisure Activities (2016), which presents average daily time spent for different household activities in Japan, reports that from 2006 to 2016, how households in Japan divide their time has changed. During this period, work and housework time decrease by 4.6% and 6.3%, respectively. Instead, households tend to spend more time on hobbies and relaxation. For example, there was a 6% increase in the time spent watching TV, listening to the radio, and reading newspapers or magazines, a 23.2% increase in time for rest, and a 3.2% increase in the time for other hobbies and amusements. Since time-saving products and services have spread rapidly during this period, these products and services may partly contribute to the change in household time allocation.

As the time-saving products tend to consume energy (or electricity), their diffusion may further accelerate energy consumption. This implies a trade-off between energy and time, through household behavior. A basic idea is as follows: On the one hand, a time-saving product newly introduced to a household helps in decreasing time spent on housework (if the amount of housework remains unchanged).

On the other hand, the increase in disposable time for the household is reallocated to other energy-using activities. For example, a dishwasher will decrease time for washing dishes (if the number of dishes or cups used remains unchanged), and the time saved may be used for cooking more and washing more dishes, or spending more time on leisure, such as TV, internet, or playing video games. These household behaviors may result in additional energy consumption. This positive effect on energy use due to the new time-saving products is called "time rebound" by Sorrell and Dimitropoulos (2008). Although time and energy are fundamental and important factors in modern economies, there are still only few studies that have examined this effect. Our present study aims at simply showing mechanisms for time rebound by considering a theoretical model of household time allocation and using it to find empirical evidence from Japanese household data.

There are many strands of literature investigating factors affecting energy use. Among them, our theoretical approach is closely related to studies on so-called the "Rebound" effect caused by energy-efficient products, an increase in energy use due to a behavioral response to improved energy efficiency of some products. Many studies refer to the generalized home production model of Becker (1975) to set econometric models, whereas Chan and Gillingham (2015) set a very simplified model of household decision-making with a linear home production. Our study follows Chan and Gillingham (2015) but integrates time as an input to a non-linear home production process. By assuming a production function in nested form, we clearly show the path to energy consumption from introducing time-saving goods through the household behavioral change on time allocation.

While many empirical studies show the existence of the rebound effect and discuss its quantitative impact, there are only a few papers on the time rebound effect. Based on time-budget survey data from six countries (Austria, Israel, the Netherlands, Sweden, United States, and West Germany), Gronau and Hamermesh (2008) show that as time efficiency of household production increases, the household will spend more time on various activities. Aguiar and Hurst (2007) and Hamermesh (2007) show that time-saving technology affects the time allocated to housework and leisure time. However, these studies have not examined how introduction of time-saving technology affects energy consumption through time allocation changes such as the time rebound effect.

The study of Brenčič and Young (2009) is the only exception; it examines the time allocation behavior of households by introducing time-saving products. They examine whether these products affect energy consumption by using the Canadian Survey of Household Energy Use data of 2003. Specifically, they present two distinct econometric models to estimate separately the coefficients of a dummy for time-saving goods [i] on time (hours per day) of housework and leisure and [ii] of a dummy for energy consumption. Although they address the presence of the time rebound effect and its significance, their findings are limited in the following points. First, since the dummy for time-saving goods is included in both models [i] and [ii], a path to energy consumption via household time allocation from introducing time-saving goods is not clear. Second, their result is qualitative but not quantitative because they are focusing only on the significance of the estimated coefficients of the time-saving goods dummy. In contrast, our econometric model explicitly considers the path from time-saving goods to energy consumption via household time allocation. Furthermore, through a calculation based on the estimated coefficients, we derive the quantitative impact of the time rebound effect as about 1.4%. The time rebound effect is thus not as large as the rebound effect in the literature[1]. However, time rebound is still significant because recent product innovations are directed to improving not only energy efficiencies but also time efficiency. Our calculated time rebound effect is not compared to the rebound effect but added to it.

The structure of our paper is as follows: In the next section, we develop a theoretical model for the time rebound effect to present a path from the introduction of time-saving technology to the change in energy consumption through household behaviors. Section 3 develops an empirical analysis of the time rebound effect. In particular, we consider a two-step econometric model: The first step is to verify the impact of time-saving goods/services on household time allocation; the second is to verify the influence of increased

[1] Sorrell et al. (2009) conclude that the size of the rebound effect of households in the OECD countries was less than 30%. Mizobuchi (2008) estimates the magnitude of the rebound effect in Japanese household sector to be about 27%

times of in-home activities on energy consumption. Section 4 explains the estimation results and calculates the magnitude of the time rebound effect using the estimated parameters. Section 5 concludes the paper.

2. Theoretical Model

The objective of this section is to present the theoretical model and show how the energy use of households is affected by time-saving goods. We set the home-production model of Becker (1965), where households enjoy services made at home with inputs that include energy. Many studies have applied this model and shown how energy use is affected by the energy-saving performance of the inputs (e.g., Berkhout et al., 2000; Greening et al., 2000; Sorrell and Dimitropoulos, 2008; Brenčič and Young, 2009). We consider time as an essential input to produce the services as well as energy. In addition, we generalize the framework as well as Chan and Gillingham (2015) to clearly present a relationship between energy use and products' time-saving performance.

2.1. Settings

A representative household has preferences over a numeraire good (C) and two types of services (X_i for $i = 1,2$). Its utility function is written as

$$U = C + u(X_1, X_2), \qquad (1)$$

where $\frac{\partial u}{\partial X_i} = u_i \geq 0$ and $\frac{\partial^2 u}{\partial X_i^2} = u_{ii} \leq 0$. Service i is a type of in-home housework, such as washing dishes and clothes, cleaning rooms, or cooking. The service can also be regarded as in-home leisure, such as reading, net surfing, or playing games.

Service i is completed using effective energy or electricity (E_i) and effective time (T_i) as inputs:

$$X_i = f_i(E_i, T_i). \qquad (2)$$

We assume that f_i in (2) is increasing in each input and exhibits homogeneousness of degree one, i.e., $\frac{\partial f_i}{\partial Z_i} = f_{i,Z} \geq 0$ and $\frac{\partial^2 f_i}{\partial Z_i^2} = f_{i,ZZ} \leq 0$ for $Z = \{E, T\}$. The effective inputs are processed through

$$E_i = g_i(e_i; \epsilon_i), \qquad (3)$$

$$T_i = h_i(t_i; \theta_i), \qquad (4)$$

where e_i and t_i are raw inputs for E_i and T_i, respectively. ϵ_i and θ_i are the productivity parameters for service i. g_i and h_i are increasing concave functions, that is, $\frac{dg_i}{de_i} = g_i^{'} \geq 0, \frac{d^2 g_i}{de_i^2} = g_i^{''} \leq 0$, $\frac{dh_i}{dt_i} = h_i^{'} \geq 0$, and $\frac{d^2 h_i}{dt_i^2} = h_i^{''} \leq 0$. We assume that larger productivity parameters imply greater production ceteris paribus, that, $\left.\frac{\partial g_i}{\partial \epsilon_i}\right|_{e_i = \bar{e}_i} \geq 0$ and $\left.\frac{\partial h_i}{\partial \theta_i}\right|_{t_i = \bar{t}_i} \geq 0$.

The household divides its total time ($T > 0$) between labor (L) and two types of activities (t_i for $i = 1,2$), which produce service i.

$$T = L + \sum_{i=1}^{2} t_i. \qquad (5)$$

The budget of the household is given as

$$wL + N = C + pe + \sum_{i=1}^{2} w_i t_i, \qquad (6)$$

where e is the total amount of energy use:

$$e = \sum_{i=1}^{2} e_i. \qquad (7)$$

N, w, w_i, and p are the non-wage income, wage rate, specific opportunity cost of activity time for service i (if any), and energy price, respectively.

2.2 Utility Maximization

We divide the household's utility maximization problem in two steps to clarify the effects of productivity parameters later. First, we consider an expenditure minimization problem related to home production under given demand for x_i: $\min_{e_i, t_i} pe_i + v_i t_i$, s.t., $X_i = f_i\big(g_i(e_i; \epsilon_i), h_i(t_i; \theta_i)\big)$ and $v_i \equiv w + w_i$. The first-order conditions are

$$p - \lambda_i \cdot f_{i,E} \cdot g_i^{'} = 0, \qquad (8)$$

$$v_i - \lambda_i \cdot f_{i,T} \cdot h_i^{'} = 0, \qquad (9)$$

where λ_i is the Lagrangean multiplier of this problem. The factor demands are given as $e_i^* = D_i^e(v_i, p, X_i; \theta_i, \epsilon_i)$ and $t_i^* = D_i^t(v_i, p, X_i; \theta_i, \epsilon_i)$. By substituting these demand functions into the object function, the minimized expenditure is derived as $\omega_i^* X_i$ where

$$\omega_i^* = \omega_i(v_i, p; \theta_i, \epsilon_i) \qquad (10)$$

is the unit cost to produce one unit of service i. As f_i in (2) exhibits homogeneousness of degree one, we have the following from Shepard's lemma:

$$e_i^* = D_i^e(v_i, p, X_i; \theta_i, \epsilon_i) = \frac{\partial \omega_i(v_i, p; \theta_i, \epsilon_i)}{\partial p} X_i, \qquad (11)$$

$$t_i^* = D_i^t(v_i, p, X_i; \theta_i, \epsilon_i) = \frac{\partial \omega_i(v_i, p; \theta_i, \epsilon_i)}{\partial w_i} X_i. \qquad (12)$$

Secondly, we consider the utility maximization with respect to the services produced at home: $\max_{C, X_1, X_2} (1)$, s.t., $I = C + \sum_{i=1}^{2} \omega_i X_i$, where I is disposable income ($I \equiv N + wT$). By setting μ as a Lagrangean multiplier of this problem, the first-order conditions are derived as follows:

$$\mu = 1, \qquad (13)$$

$$u_i - \mu \omega_i = 0. \qquad (14)$$

The demand for service i is

$$X_i^* = x_i(\omega_1, \omega_2, I). \qquad (15)$$

2.3 Energy use

We assume that the time-saving efficiency parameter for service 1 is increased by θ_1. This section then examines how energy use is affected by θ_1. Following the literature on rebound effect, we show the change in energy use in elasticity form.

Differentiating (7) with respect to θ_1 yields (See Appendix A for derivation):

$$\eta_{\theta_1}^{e} \equiv \frac{\theta_1}{e^*} \cdot \frac{\partial e^*}{\partial \theta_1} = \underbrace{s_1 \, \bar{\eta}_{\theta_1}^{e_1}}_{\text{Direct effect}} + \overbrace{\underbrace{s_1 \eta_{\omega_1}^{X_1} \eta_{\theta_1}^{\omega_1}}_{\text{Direct time rebound}} + \underbrace{s_2 \eta_{\omega_1}^{X_2} \eta_{\theta_1}^{\omega_1}}_{\text{Indirect time rebound}}}^{\text{Time rebound effect}}. \qquad (16)$$

The change in energy use is divided into three effects. Each of them is weighted by its portion of energy use by service ($s_i = e_i/e$ and $s_1 + s_2 = 1$). The first term of RHS is the "direct effect," the primary effect of time-saving efficiency on energy use when the household demand for service 1 does not change. As an example, let us suppose that service 1 is cooking. Direct effect then implies that a microwave oven instead of a traditional oven may contribute to saving not only cooking time but also energy use in home cooking if the household does not change its frequency of home cooking.[2]

The last two terms in (16) are effects on energy use through a change in household behavior. The second term is the "direct time rebound effect," a change in energy use via self-price substitution. The self-price substitution occurs because the increased efficiency of the time-saving goods decreases the unit cost, ω_1, which is the unit cost of producing service 1, that is, $\eta_{\theta_1}^{\omega_1} \leq 0$. As the self-price substitution is typically negative in standard demand theory, that is, $\eta_{\omega_1}^{X_1} \leq 0$, the direct time rebound effect tends to increase energy use. Let us suppose service 1 is washing clothes. Then, this path can be interpreted to mean that a household with a clothes dryer washes clothes more frequently than a household without it.

Finally, the third term is the "indirect time rebound effect," a change in energy use via the cross-price substitution effect between services 1 and 2. Time-saving goods with a higher efficiency decrease the unit cost of service 1 and increase the relative price of service 2, which yields the cross-price substitution. The energy use decreases if service 1 and 2 are gross complements, whereas it increases if they are gross substitutes. If services 1 and 2 are cleaning a room and watching a video, respectively, a household with an automatic vacuum cleaner may save time on cleaning rooms and its inhabitants may enjoy watching more videos. This is an example in which the two services are gross substitutes. Cooking and dish washing may be an example of gross complements. Comparing households with and without a dishwasher, the one with the dishwasher may cook more frequently than the one without it and increase energy use.

[2] Direct effect is straightforward when the energy efficiency is improved as much as is stated in the literature on rebound effect. Direct effect is a decrease in energy use when households do not change their way of using the products. However, as the present study examines the impact of the time-saving efficiency on energy consumption, this term does not necessarily imply a decrease in energy used.

The standard rebound effect from an increase in the energy efficiency of goods has been repeatedly examined in the literature. Eq. (16) shows that energy consumption is affected not only from the energy efficiency of the goods but also from the time-saving efficiency through household behavior. In the next section, we will verify this time rebound effect by using Japanese household data.

3. Empirical Analysis

3.1.Empirical Model

The theoretical model presents the path to a change in energy consumption stemming from improved time-saving efficiency via direct effect, direct time rebound, and indirect time rebound. Although the qualitative and quantitative impact of these effects is not clear, the theoretical model shows that energy consumption may increase if the time saved by the time-saving goods is reallocated to energy-using activities. This section empirically determines the existence of the time rebound effect and its magnitude.

Our empirical analysis assesses whether the time rebound effect occurs or not by considering a two-step empirical model. Although we follow Brenčič and Young (2009) in setting two empirical models, our model allows for the path to a change in the energy consumption from introducing the time-saving goods by setting the two models in a stepwise fashion. In the first step, the following econometric model verifies whether the introduction of the time-saving technology causes a reallocation of time use at home:

$$time\ use_i = \beta_0 + \sum_j \ \beta_j\ timesaving\ goods_j + \beta^{\prime}\ X + u. \qquad \text{(i)}$$

Here, “time use” is the time used for housework and leisure, such as cleaning, laundry, and TV viewing; "time-saving goods" represents a dishwasher, clothes dryer, vacuum cleaner, net ordering/delivery service, and the like. X is an explanatory variable vector of household attributes, and u is the error term. If the introduction of the time shortening technology affects housework or leisure time, the estimated parameter of β_j becomes significant.

The second step is for verifying the effect on energy consumption through the time reallocation to each activity. If households spend more time on energy-consuming activities, the total energy consumption increases. This will be verified by estimating the following econometric model:

$$energy\ usage/day = \gamma_0 + \sum_i \gamma_i\ time\ use_i + \gamma' Y + \epsilon. \qquad \text{(ii)}$$

Here, "energy usage/day" is the electricity consumption per day; "time use" is the dependent variable of the estimated model in (i). The explanatory variable vector Y includes air temperature, home appliance holding status, and the like; ϵ is the error term. This stepwise empirical model can provide an important insight on the effect on energy consumption by capturing a household's decision-making with regard to time allocation. Alternatively, significant results in both models provide an estimation of the time rebound effect. Here, *time use* in model (ii) must be an exogenous variable, but it is actually determined endogenously by model (i). Therefore, if both models are estimated separately, the problem of endogeneity occurs in γi in model (ii). For this reason, we simultaneously estimate both empirical models of (i) and (ii).

3.2.Data

We surveyed households in the Kansai area[3] about their electricity usage on-line.[4] Almost all households in the Kansai area purchased electricity from Kansai Electric Power Co., Inc. (KEPCO) in February 2016 according to our survey. KEPCO provides their customers with online-accessible data on their monthly electricity consumption for the previous two-year period. We requested the household

[3] The Kansai area comprises the Osaka, Kyoto, Hyogo, Nara, Shiga, and Wakayama prefectures.
[4] The data was collected by an online survey company. This company has its own registered households and asked those situated in the Kansai area to participate in the survey. The participating households were selected on a first-come, first-served basis, until their total number reached 715.

residents to download and submit these data to us.[5] Out of 715 households, 646 provided both their monthly electricity consumption data and the questionnaire data. Although the electricity consumption data are monthly, we built seasonal data and used them for the empirical analysis. This was done because the dates of reading meters for electricity usage vary by households, that is, important factors affecting electricity usage, such as weather, outside temperature, number of holidays, and other conditions vary by households.

In this article, we take into account dishwashers, automatic vacuum cleaners (Roomba), and clothes dryers as time-saving technology; and net order delivery services of food, daily necessities, clothing, books, and home appliances (e.g., Amazon.com and Rakuten.com) as time-saving services. The survey collected household behavioral information, including whether a household possesses time-saving goods, and the frequency of using time-saving services. The time spent on activities was also surveyed by type of activity, such as cooking, washing, and cleaning as housework, and watching television (including internet TV), surfing the internet (PC, mobile phone and tablet, etc.), playing games, reading, and other hobbies at home as leisure. Finally, we collected meteorological data, such as temperature from the Japan Meteorological Agency[6], and socioeconomic data related to households, such as the household's appliance ownership situation, and household attributes, from our questionnaire survey. Table 1 summarizes the descriptive statistics of the data.

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[5] These data are provided in Microsoft Excel file format and include not only the monthly electricity consumption, but also the date of meter reading, number of days of utilization, and the monthly electricity bill.

[6] http://www.jma.go.jp/jma/indexe.html

Table 1. Descriptive statistics

Variable	contents	Mean	Std.Dev.	Min	Max
e_annual	kWh/day	12.803	9.533	0	61.34
e_spring	kWh/day	10.472	7.647	0	50.93
e_summer	kWh/day	11.583	6.991	0	49.76
e_autumn	kWh/day	10.943	7.933	0	50.53
e_winter	kWh/day	15.414	12.466	0	88.12
t_annual	˚C	16.539	1.954	3.80	23.33
t_spring	˚C	17.021	1.648	6.64	22.30
t_summer	˚C	26.364	1.368	7.18	28.78
t_autumn	˚C	16.321	1.962	5.63	24.04
t_winter	˚C	6.865	1.256	2.76	9.66
dish_w (dummy)	yes/no	0.273	0.446	0	1
roomba (dummy)	yen/no	0.056	0.230	0	1
cloth_d (dummy)	yes/no	0.179	0.384	0	1
net_food*1	purchase online(food)	2.385	1.184	1	5
net_medical*1	purchase online(medical)	2.276	1.071	1	5
net_cloth*1	purchase online(clothes)	2.246	1.023	1	5
net_book*1	purchase online(book)	2.383	1.088	1	5
net_home_app*1	purchase online(home appliances)	2.497	0.979	1	5
net_use_freq (sum of above five)	above five total values	11.786	4.141	5	25
age	age	49.291	9.006	26	65
income*2	income	7.038	3.293	1	12
people	number of family members	2.762	1.323	1	7
children	number of children	0.586	0.872	0	5
wide*3	size of house	3.303	1.404	1	6
detached (dummy)	yes/no	0.536	0.499	0	1
all electrification (dummy)	yen/no	0.267	0.443	0	1
solar panel (dummy)	yes/no	0.126	0.332	0	1
air_n	owned number	2.762	1.750	0	9
tv_n	owned number	1.908	1.185	0	9
ref_n	owned number	1.171	0.490	0	4
cooking*4	time/day	1.586	0.831	0	6
washing*5	times/week	5.020	2.273	0	7
clean*5	times/week	2.909	2.515	0	7
tv*6	time/day	5.144	2.846	0	18
net*7	time/day	6.973	4.007	0	22
game*8	time/day	1.646	2.219	0	11
reading*8	time/day	1.491	1.698	0	11
other hobby in home*8	time/day	2.887	2.412	0	11

*1 frequency of use (5: very often, 4: often, 3: sometimes, 2: seldom, 1: never)

*2 1: under 1 million yen, 2: 1-2 million yen, 3: 2-3 million yen, 4: 3-4 million yen, 5: 4-5 million yen, 6: 5-6 million yen, 7: 6-7 million yen, 8: 7-8 million yen, 9: 8-9 million yen, 10: 9-10 million yen, 11: 10-15 million yen, 12: over 15 million yen

*3 1: under 30 ㎡, 2: 31-60 ㎡, 3: 61-90 ㎡, 4: 91-120 ㎡, 5: 121-150 ㎡, 6: over 151 ㎡

*4 0: never, 1: under 1 hour, 2: 1-2 hours, 3: 2-3 hours, 4: 3-4 hours, 5: 4-5 hours, 6: over 5 hours (per day),

*5 0: never, 1: one time/week, 2: two times/week, 3: three times/week, 4: four times/week, 5: five times/week, 6: six times/week, 7: everyday

*6 0: never, 1: under 1 hour, 2: 1-2 hours, 3: 2-3 hours, 4: 3-4 hours, 5: 4-5 hours, 6: 5-6 hours, 7: 6-7 hours, 8: 7-8 hours, 9: 8-9 hours, 10: 9-10 hours, 11: 10-11 hours, 12: 11-12 hours, 13: 12-13 hours, 14: 13-14 hours, 15: 14-15 hours, 16: 15-16 hours, 17: 16-17 hours, 18: over 17 hours (per day)

*7 0: never, 1: under 0.5 hours, 2: 0.5-1 hours, 3: 1-1.5 hours, 4: 1.5-2 hours, 5: 2-2.5 hours, 6: 2.5-3 hours, 7: 3-3.5 hours, 8: 3.5-4 hours, 9: 4-4.5 hours, 10: 4.5-5 hours, 11: 5-5.5 hours, 12: 5.5-6 hours, 13: 6-6.5 hours, 14: 6.5-7 hours, 15: 7-7.5 hours, 16: 7.5-8 hours, 17: 8-8.5 hours, 18: 8.5-9 hours, 19: 9-9.5 hours, 20: 9.5-10 hours, 21: 10-10.5 hours, 22: over 10.5 hours (per day)

*8 0: never, 1: under 0.5 hours, 2: 0.5-1 hours, 3: 1-1.5 hours, 4: 1.5-2 hours, 5: 2-2.5 hours, 6: 2.5-3 hours, 7: 3-3.5 hours, 8: 3.5-4 hours, 9: 4-4.5 hours, 10: 4.5-5 hours, 11: over 5 hours (per day)

We look at the relationship between the various household activities. Table 2 shows the correlation coefficient matrix of 8 in-home activities (three housework activities and five leisure ones) from the survey. A positive correlation can be confirmed for three pairs of housework activities (0.322 for cooking and laundry, 0.225 for cooking and cleaning, and 0.437 for washing and cleaning). This result implies that the households spending much time on certain housework activities also tend to spend much time on other housework activities. On the other hand, the correlation between the three housework and five leisure activities is not that high. Further, a negative correlation can be seen between two housework activities and Internet browsing, which shows that internet browsing may interfere with housework. Positive correlations between the five leisure activities may represent a tendency that one leisure encourages households to do other leisure activities. For example, this tendency seems strong between watching TV and browsing internet, or between browsing internet and playing video games. From Table 2, our empirical analysis assumes that the time saved by the introduction of time-saving goods will be allocated to these five in-home activities.

Table 2. Correlation matrix of in-home behavior activities

	cooking	washing	clean up	tv	net	game	reading	other hobby
cooking	1.000							
washing	0.322	1.000						
clean up	0.225	0.437	1.000					
tv	0.153	0.040	0.073	1.000				
net	0.014	-0.071	-0.064	0.303	1.000			
game	0.037	0.136	0.049	0.089	0.239	1.000		
reading	0.086	0.082	0.086	0.047	0.210	0.325	1.000	
other hobby	0.022	0.014	-0.003	0.169	0.318	0.134	0.217	1.000

4. Results and Discussion

We verify the time rebound effect by using the two-step empirical model presented in (i) and (ii). These models are used to derive (i) the effect of introducing the time-saving technology on the time spent on the various household activities and (ii) the effects of time spent on the various household activities on energy (electricity) consumption. The two empirical models are estimated simultaneously by iterated Seemingly Unrelated Regressions (SUR). The dependent variable of model (ii) deals with five cases, which are the values of “e_annual,” “e_spring,” “e_summer,” “e_fall,” and “e_winter” in Table 1. Table 3 and Table 4, to be described later, present the results using “e_annual” as the dependent variable for the model (ii). Results using seasonal electricity usage are listed in Table A.

4.1.Impact on housework

Table 3 shows the estimated coefficients of model (i), which exhibit the impacts of introducing time-saving goods and services on the time spent on three housework activities: as cooking, clothes washing, and cleaning. For comparison, the results obtained by estimating each model separately by OLS are also shown in this table. Model (i) shows that the simultaneously estimated values are close to the OLS estimated values. Based on the results, the households that own a dishwasher significantly increase their washing time compared to the households that do not. Likewise, the households using net ordering/delivery services significantly increase their room-cleaning time. That is, the time saved by the time-saving goods and services has been reallocated to the other activities at home. Although our result is consistent with that in Brenčič and Young (2009), they have not verified the impact of this time allocation change on energy consumption. Our paper examines it in section 4.3. The number of family members significantly increases all housework activities. It may be obvious for households with many members that much time has to be devoted to housework such as cooking, laundry, and room cleaning.[7]

4.2.Impact on leisure time

[7] In Japan, hiring housekeepers at individual levels to outsource housework is not common. If the survey were conducted in countries where there are competitive supplies of housekeepers and households are habituated to this service, the results will be different. In this case, household income will have to be carefully examined.

Next, we examine the time reallocation to leisure in light of the results from model (i). Table 4 shows the influence of the time-saving goods and services on the time spent on five leisure activities: watching television, surfing the internet, playing games, reading, and doing other leisure activities at home. From the estimation results, there exists a significant effect of time reallocation to many leisure activities. Clothes dryers increase reading time. The use of a net ordering/delivery service has a large positive impact on the time for the five aforementioned leisure activities. These results imply that shopping time is shortened using a net ordering/delivery service; instead, the time saved is spent on hobbies and leisure at home.

Regarding household attributes, the age of the respondent significantly decreases the time for video games. The number of family members and children are also significantly affect leisure time. Specifically, the more children a household has, the less is the time allocated to leisure.

Table 3. Estimation results (time allocation to housework activities)

	cooking		washing		clean	
	OLS	iterated SUR	OLS	iterated SUR	OLS	iterated SUR
dish_w	0.087	0.081	0.513 ***	0.533 ***	0.085	0.116
	[.070]	[.084]	[.151]	[.186]	[.231]	[.241]
roomba	-0.112	-0.125	-0.137	-0.104	0.094	0.396
	[.124]	[.154]	[.254]	[.340]	[.400]	[.442]
cloth_d	0.043	0.005	0.338 **	0.291	-0.038	0.062
	[.074]	[.092]	[.171]	[.203]	[.232]	[.264]
net_use_freq	0.004	0.009	0.027 *	0.025	0.049 **	0.055 **
	[.007]	[.009]	[.016]	[.019]	[.022]	[.024]
age	-0.003	-0.003	0.011	0.010	0.038 ***	0.045 ***
	[.004]	[.004]	[.009]	[.010]	[.010]	[.013]
income	0.017 *	0.018	0.019	-0.007	0.055 **	0.047
	[.009]	[.011]	[.022]	[.025]	[.028]	[.032]
people	0.198 ***	0.219 ***	0.884 ***	0.945 ***	0.485 ***	0.446 ***
	[.036]	[.040]	[.079]	[.088]	[.104]	[.114]
children	-0.062	-0.077	0.128	0.135	0.223	0.298 *
	[.057]	[.060]	[.104]	[.132]	[.162]	[.172]
cons	1.019 ***	0.918 ***	1.302 ***	1.345 ***	-1.428 **	-1.793 **
	[.202]	[.248]	[.481]	[.548]	[.574]	[.712]
Number of obs	715	550	715	550	715	550
R-squared	0.104	0.109	0.378	0.390	0.142	0.145

The dependent variable in model (ii) is "e_annual" (see Table A for seasonal results).

Standard errors are given within parentheses.

***, **, ** represent statistical significance at the 1%, 5%, and 10% levels, respectively.

Table 4. Estimation results (time allocation to leisure at home)

	tv		net		game		reading		othre hobby	
	OLS	iterated SUR	OLS	iterated SUR	OLS	iterated SUR	OLS	iterated SUR	OLS	iterated SUR
dish_w	-0.245	-0.282	-0.006	0.003	0.108	0.081	-0.296 *	-0.287 *	-0.088	-0.289
	[.237]	[.287]	[.371]	[.413]	[.220]	[.216]	[.154]	[.169]	[.203]	[.242]
roomba	-0.067	-0.260	-0.522	-0.365	0.005	0.096	0.243	0.144	0.274	0.294
	[.375]	[.526]	[.665]	[.756]	[.311]	[.396]	[.248]	[.309]	[.320]	[.443]
cloth_d	0.352	0.370	-0.402	-0.660	0.074	0.316	0.322 *	0.354 *	-0.367 *	-0.319
	[.265]	[.314]	[.411]	[.452]	[.197]	[.237]	[.168]	[.185]	[.221]	[.265]
net_use_freq	0.051 *	0.037	0.106 ***	0.098 **	0.066 ***	0.064 ***	0.092 ***	0.094 ***	0.092 ***	0.086 ***
	[.027]	[.029]	[.038]	[.042]	[.019]	[.022]	[.018]	[.017]	[.022]	[.024]
age	0.015	0.005	0.003	-0.014	-0.025 ***	-0.038 ***	0.010	0.002	0.025 **	0.012
	[.012]	[.015]	[.020]	[.022]	[.009]	[.011]	[.008]	[.009]	[.010]	[.013]
income	-0.026	0.002	-0.102 **	-0.109 **	-0.050 *	-0.053 *	0.017	0.019	-0.032	-0.070 **
	[.036]	[.038]	[.047]	[.055]	[.028]	[.029]	[.018]	[.023]	[.031]	[.032]
people	0.664 ***	0.705 ***	0.263	0.176	0.357 ***	0.353 ***	0.190 ***	0.201 **	0.138	0.192 *
	[.123]	[.136]	[.172]	[.195]	[.078]	[.102]	[.069]	[.080]	[.099]	[.114]
children	-0.797 ***	-0.946 ***	-0.485 *	-0.600 **	0.105	-0.037	-0.077	-0.154	-0.294 **	-0.355 **
	[.172]	[.204]	[.268]	[.294]	[.143]	[.154]	[.105]	[.120]	[.145]	[.172]
cons	2.656 ***	3.121 ***	5.960 ***	7.346 ***	1.346 **	2.111 ***	-0.652	-0.285	0.673	1.569 **
	[.639]	[.847]	[1.122]	[1.217]	[.620]	[.637]	[.460]	[.497]	[.579]	[.713]
Number of obs	715	550	715	550	715	550	715	550	715	550
R-squared	0.065	0.067	0.024	0.029	0.095	0.092	0.084	0.080	0.046	0.045

The dependent variable in model (ii) is “e_annual” from Table 1 (see Table A for seasonal results).

Standard errors are given within parentheses.

***, **, ** represent statistical significance at the 1%, 5%, and 10% levels, respectively.

4.3.Impact on electricity usage

From the results in Tables 3 and 4, time-saving goods and services clearly change households’ behavior related to time use. If the time saved results in an increase in energy consumption, this implies a time rebound effect. To determine its existence, this section considers the results of model (ii) and shows how much a household’s behavioral change regarding time use affects energy consumption.

Table 5 shows the estimation results of empirical model (ii). Since electricity consumption varies greatly by season, we include the respective estimation results. Empirical model (ii) includes the household attributes explanatory variables (age, income, and family size) and house attributes (size of house, whether it is owned or not, all-electric, installation of solar panels), the number of household appliances (air-conditioner, TV, refrigerator), and the average temperature. The results for these variables in our model are consistent with those in previous studies.

Based on the estimation results, we can confirm that the time spent on washing, television, and video game significantly increases electricity usage. Considering Table 5 along with Table 4, which presents a significant change in these three in-home activities,[8] the time rebound effect does occur with respect to washing clothes, viewing television, and playing video games.

The time rebound effect of washing clothes is evaluated by the availability of a dishwasher, whereas the time rebound effect of watching television and playing video games stems from a net order/delivery service. From Table 5, the direct change in energy consumption (i.e., the direct effect in equation (16)) can also be identified separately from the time rebound effect. Since the estimation coefficient of dishwasher (dish_w) is positive and significant, separate from the time rebound effect, a direct effect in equation (16) can be confirmed from the use of this time-saving good.

Brenčič and Young (2009) verify the existence of the time rebound effect by directly introducing a dummy variable for time-saving goods as an explanatory variable for electricity consumption. Their approach, however, does not exclude the direct effect of time-saving goods and services themselves consuming electricity. As shown in (16), the time rebound effect occurs via the household behavior on time allocation. Therefore, the time rebound effect should be separately estimated from the direct effect by identifying the reallocation effect of time. Our present study successfully reveals such an effect from the time redistribution to some home behaviors by adopting the two-step empirical model.

Furthermore, we can interpret the estimation results by dividing the time rebound effect into direct and indirect effects as shown in (16). The time rebound effect on home laundry service contains the indirect path. When a dishwasher is introduced, although it is directly related to home cooking, the time spent on laundry indirectly increases (see Table 3). Consequently, this leads to an increase in electricity use (see Table 5). Likewise, the time rebound effect on television and games is the indirect rebound effect from the use of a net ordering/delivery service. On the other hand, the direct time rebound effect is not observed as a significant estimator in our analysis.

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[8] Television viewing is also significant in the seasonal estimation, shown in Table A.

Table 5. Estimation results (impact on electricity usage)

	annual		spring		summer		autumn		winter	
	OLS	iterated SUR	OLS	iterated SUR	OLS	iterated SUR	OLS	iterated SUR	OLS	iterated SUR
cooking	-0.335	-0.225	0.044	0.142	-0.294	-0.338	0.121	0.275	-0.324	0.002
	[.279]	[.314]	[.226]	[.242]	[.241]	[.228]	[.235]	[.244]	[.369]	[.397]
washing	0.368 ***	0.343 **	0.235 **	0.210 *	0.161	0.177 *	0.160	0.143	0.345 *	0.265
	[.136]	[.147]	[.112]	[.111]	[.111]	[.105]	[.117]	[.113]	[.189]	[.181]
clean	0.161	0.088	-0.014	-0.005	0.016	0.051	-0.005	-0.125	-0.033	-0.247 *
	[.127]	[.111]	[.094]	[.086]	[.089]	[.080]	[.095]	[.086]	[.148]	[.138]
tv	0.153 *	0.287 ***	0.182 **	0.224 **	0.151 **	0.096	0.203 **	0.479 ***	0.227 *	0.637 *
	[.083]	[.095]	[.072]	[.073]	[.067]	[.070]	[.082]	[.075]	[.126]	[.119]
net	0.056	0.059	0.042	0.038	0.045	0.043	0.020	0.020	0.004	-0.004
	[.076]	[.068]	[.060]	[.053]	[.054]	[.049]	[.062]	[.053]	[.095]	[.086]
game	0.041	0.028	0.070	0.072	0.173 **	0.186 **	0.110	0.046	0.089	-0.006
	[.124]	[.123]	[.100]	[.095]	[.086]	[.089]	[.096]	[.096]	[.152]	[.155]
reading	-0.052	-0.001	-0.050	0.001	-0.176	-0.194	-0.037	0.052	-0.030	0.099
	[.161]	[.161]	[.131]	[.127]	[.137]	[.123]	[.141]	[.132]	[.203]	[.207]
other hobby	-0.043	-0.004	0.072	0.057	0.104	0.081	0.104	0.178 **	0.111	0.199
	[.091]	[.112]	[.082]	[.084]	[.079]	[.080]	[.105]	[.086]	[.160]	[.140]
dish_w	0.786	0.886	0.726	0.978 **	0.961 *	0.914 **	1.164 **	1.403 ***	1.659 *	1.943 **
	[.740]	[.625]	[.572]	[.472]	[.525]	[.451]	[.581]	[492]	[.953]	[.779]
roomba	-0.998	-0.925	-0.963	-0.929	-0.772	-0.805	-0.234	-0.294	-0.467	-0.324
	[1.012]	[1.102]	[.770]	[.824]	[.798]	[.774]	[.917]	[.835]	[1.489]	[1.378]
cloth_d	0.055	0.017	0.129	0.231	0.356	0.372	0.415	0.367	0.542	0.416
	[.697]	[.661]	[.593]	[.502]	[.569]	[.476]	[.624]	[.520]	[1.061]	[0.835]
net_use_freq	0.011	0.003	0.022	0.023	0.066	0.076 *	0.063	0.044	0.010	-0.009
	[.058]	[.063]	[.048]	[.047]	[.047]	[.044]	[.051]	[.048]	[.081]	[.077]
cons	-6.566 **	-7.095 **	-3.081	-6.625 ***	-11.302 ***	-10.430 ***	-6.214 ***	-11.342 ***	-8.311 ***	-9.606 **
	[3.065]	[3.418]	[2.586]	[2.433]	[4.352]	[2.495]	[2.135]	[2.539]	[2.939]	[3.943]
Number of obs	550	550	650	660	647	653	658	658	646	647
R squared	0.643	0.640	0.636	0.619	0.590	0.593	0.639	0.629	0.626	0.615

Standard errors are given within parentheses.

***, **, ** represent statistical significance at the 1%, 5%, and 10% levels, respectively.

We also include age, income and family size, size of house, whether it is owned or not, all electrification, installation of solar panels, number of household appliances (air-conditioner, TV, and refrigerator), and average temperature as the explanatory variables. The presentation of their estimated coefficients is omitted.

4.4. Magnitude of the time rebound effect

The discussion so far clearly shows the time rebound effect in two time-saving products/services (i.e., dishwasher and net ordering/delivery). This section estimates the magnitude of the time rebound effect generated from each time-saving good by using the parameters estimated in Tables 3, 4, 5, and A.

First, we calculate the increase in the time spent on in-home activities stemming from introducing each time-saving good (i.e., dishwasher and net ordering/delivery) by using the estimated parameters in Tables 3, 4, and A. Next, by multiplying the calculated values with the estimated parameters of in-home activity time in Table 5, we derive how much the energy consumption has increases.[9]

Table 6 shows the results for each time-saving product/service. In the upper half of the table, the magnitude of the "direct effect," "direct time rebound effect," and "indirect time rebound effect" of equation (16) is given as electricity usage (kWh / day). The lower half of the table are the values of the "direct time rebound effect" and "indirect time rebound effect" from the upper half of the table divided by the average electricity usage of the day. From our calculations, the magnitude of the time rebound effect for all time-saving products/services appears to be small. Specifically, it is 0.80% - 1.43% for dishwasher and 0.10% - 0.26% for net ordering/delivery, and even when two sets are summed up, it is 0.12% - 1.43%.[10] Further, the "direct effect" occurs only in the dishwasher, and if this influence is included, consumption will rise by approximately 8% - 11%, depending on the season.

Table 6. Time rebound effect

Dish washer

	annual	spring	summer	autumn	winter
direct effect (kWh/day)	0.00	0.00	0.96	1.16	1.66
direct time rebound effect (kWh/day)	0.00	0.00	0.00	0.00	0.00
indirect time rebound effect (kWh/day)	0.18	0.11	0.09	0.00	0.00
average electricity usage (kWh/day)	12.80	10.47	11.58	10.94	15.41
direct effect (%)	0.00	0.00	8.32	10.64	10.76
direct time rebound effect (%)	0.00	0.00	0.00	0.00	0.00
indirect time rebound effect (%)	1.43	1.07	0.80	0.00	0.00
Total time rebound effect (%)	1.43	1.07	0.80	0.00	0.00

Net ordering/delivery

	annual	spring	summer	autumn	winter
direct effect (kWh/day)	0.00	0.00	0.00	0.00	0.00
direct time rebound effect (kWh/day)	0.00	0.00	0.00	0.00	0.00
indirect time rebound effect (kWh/day)	0.00	0.01	0.01	0.03	0.02
average electricity usage (kWh/day)	12.80	10.47	11.58	10.94	15.41
direct effect (%)	0.00	0.00	0.00	0.00	0.00
direct time rebound effect (%)	0.00	0.00	0.00	0.00	0.00
indirect time rebound effect (%)	0.00	0.12	0.10	0.26	0.12
Total time rebound effect (%)	0.00	0.12	0.10	0.26	0.12

[9] The size of the time rebound effect is calculated as $E_{add} / E_{total} \times 100$, where E_{add} is an additional electricity usage (kWh/day) from the introduction of the time-saving good, and E_{total} is the average electricity usage (kWh/day).

[10] The time rebound of net ordering/delivery is evaluated by assuming that usage frequency is increased by 1.

5. Conclusion

In recent years, people have been able to benefit from the development and spread of time-saving technology. However, this may increase energy consumption through household behaviors as a time rebound effect. This study examines the time rebound effect from both a theoretical and empirical perspective.

Our theoretical approach sets a model where a household spends time and energy as inputs on producing services to be consumed. The time-saving goods are adopted to save the household's time for the production. By assuming a productivity increase from a time-saving goods, we present three effects on energy consumption as a direct effect, a direct time rebound effect, and an indirect time rebound effect. The direct effect is the change in energy consumption when the household does not change its behavior. In contrast, both time rebound effects are the changes in energy consumption when the household changes its behavior. The direct time rebound effect is a change in energy use when the household changes its behavior in adopting the time-saving good and its productivity increases. The indirect rebound effect is a change in energy use when the household changes its behavior in adopting other time-saving goods even if its productivity remains unchanged.

Moreover, our empirical model clearly verifies the existence of the time rebound effect while identifying its path by using the survey data from approximately 700 Japanese households. More specifically, we estimate the direct increase in energy consumption by introducing time-saving technology via a change of household behaviors in time allocation. We target three home appliances (dishwasher, clothes dryer, and automatic vacuum cleaner) and one service (net ordering/delivery) as time-saving goods and services. In addition, as household behavior, we target three household chores (cooking, laundry, and cleaning) and five leisure activities (television, internet, games, reading, and other home hobbies). Hence, we reveal that the introduction and utilization of time-saving goods and services cause significant changes in the time spent on household behaviors. Furthermore, the time-saving technology significantly increases the amount of electricity use, partly due to the significant change in household behaviors, namely the time rebound effect. According to our calculations, the magnitude of the time rebound effect is not substantially large, at about 1.4% of the daily electricity use. However, we can deduce that time-saving goods and services will be increasingly diffused and diversified. Because the calculated result is only the tip of the iceberg in the short term, the time rebound effect must become much more important in the long term.

Finally, the result in our study implies that time-saving goods and services do not necessarily increase household electricity consumption. For example, on the one hand, a dishwasher increases the electricity consumption by its usage, but on the other hand, it helps in reducing the water used compared to that for the conventional hand washing method. The use of a net ordering/delivery service may imply smaller transportation energy use than the individual level (e.g., gasoline when using a car) because of efficient logistic networks, which is not studied in our estimation of electricity consumption[11].

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[11] Reduction of the transportation energy of each household implies an increase in the transport energy of the delivery company. In general, however, it is considered that the energy efficiency of delivery is higher for bulk delivery by shippers than that of the total extra energy that would otherwise have been expended by individual households.

Table A. Estimation results of simultaneous equation model for each season (time allocation to housework and leisure in home) with iterated SUR.

	cooking	washing	clean	tv	net	game	reading	othre hobby
dish_w								
spring	0.072	0.535 ***	0.130	-0.282	-0.077	0.168	-0.205	-0.120
	[.076]	[.169]	[.217]	[.259]	[.375]	[.197]	[.149]	[.222]
summer	0.075	0.525 ***	0.102	-0.370	-0.073	0.195	-0.241	-0.077
	[.077]	[.172]	[.222]	[.260]	[.383]	[.200]	[.146]	[.226]
fall	0.073	0.517 ***	0.081	-0.347	-0.020	0.200	-0.243	-0.067
	[.078]	[.172]	[.223]	[.260]	[.380]	[.200]	[.146]	[.225]
winter	0.085	0.506 ***	0.126	-0.283	-0.032	0.133	-0.214	-0.152
	[.076]	[.171]	[.220]	[.262]	[.375]	[.198]	[.150]	[.221]
roomba								
spring	-0.082	-0.172	0.309	-0.235	-0.498	0.110	0.329	0.191
	[.137]	[.306]	[.393]	[.469]	[.679]	[.356]	[.270]	[.401]
summer	-0.075	-0.177	0.318	-0.200	-0.497	0.147	0.391	0.198
	[.137]	[.306]	[.395]	[.463]	[.681]	[.356]	[.261]	[.402]
fall	-0.093	-0.167	0.224	-0.073	-0.518	0.084	0.345	0.204
	[.136]	[.304]	[.392]	[.458]	[.669]	[.351]	[.258]	[.396]
winter	-0.067	-0.180	0.299	-0.218	-0.391	0.133	0.247	0.225
	[.139]	[.315]	[.406]	[.4828]	[.690]	[.364]	[.276]	[.407]
cloth_d								
spring	0.030	0.296	0.126	0.439	-0.322	0.199	0.302	-0.277
	[.083]	[.186]	[.239]	[.285]	[.413]	[.217]	[.164]	[.244]
summer	0.023	0.363	0.129	0.401	-0.398	0.089	0.162	-0.339
	[.085]	[.189]	[.244]	[.285]	[.420]	[.219]	[.160]	[.248]
fall	0.036	0.361	0.122	0.389	-0.453	0.073	0.185	-0.374
	[.085]	[.189]	[.244]	[.284]	[.416]	[.218]	[.160]	[.246]
winter	0.014	0.332	0.108	0.413	-0.466	0.166	0.311	-0.226
	[.084]	[.190]	[.245]	[.290]	[.416]	[.219]	[.167]	[.245]
net_use_freq								
spring	0.005	0.023	0.055 **	0.056 **	0.100 **	0.066 ***	0.084 ***	0.096 ***
	[.008]	[.017]	[.022]	[.026]	[.038]	[.020]	[.015]	[.024]
summer	0.004	0.024	0.046 **	0.061 **	0.104 ***	0.061 ***	0.075 ***	0.091 ***
	[.008]	[.017]	[.022]	[.026]	[.038]	[.020]	[.015]	[.023]
fall	0.004	0.025	0.049 **	0.060 **	0.104 ***	0.060 ***	0.074 ***	0.090 ***
	[.007]	[.017]	[.022]	[.026]	[.038]	[.020]	[.015]	[.022]
winter	0.005	0.020	0.051 **	0.049 *	0.096 **	0.062 ***	0.087 ***	0.089 ***
	[.005]	[.020]	[.022]	[.026]	[.038]	[.020]	[.015]	[.022]

standard errors within parentheses

***, **, ** represent statistical significance at the 1%, 5%, and 10% levels, respectively.

We also include age, income, family size, and number of children as explanatory variables. The presentation of their estimated coefficients is omitted.

Appendix A: Derivation of (16)

We derive the change in energy use induced by a discrete increase in the time-saving parameter, θ_1. As total energy demand is $e^* = \sum_{i=1}^{2} D_i^e(v_i, p, X_i; \theta_i, \epsilon_i)$ from (11), we differentiate this expression with respect to the time-saving parameter for service 1, θ_1:

$$\frac{\partial e^*}{\partial \theta_1} = \left.\frac{\partial e_1}{\partial \theta_1}\right|_{X_1=\bar{X}_1} + \frac{\partial e_1}{\partial X_1}\frac{\partial X_1}{\partial \omega_1}\frac{\partial \omega_1}{\partial \theta_1} + \frac{\partial e_2}{\partial X_2}\frac{\partial X_2}{\partial \omega_1}\frac{\partial \omega_1}{\partial \theta_1}. \qquad (\mathrm{A.1})$$

We rearrange (A.1) in elasticity forms by multiplying both sides with θ_1/e^*.

$$\left(\frac{\theta_1}{e^*}\frac{\partial e^*}{\partial \theta_1}\right) = \frac{e_1^*}{e^*}\left(\frac{\theta_1}{e_1^*}\left.\frac{\partial e_1}{\partial \theta_1}\right|_{X_1=\bar{X}_1}\right) + \frac{e_1^*}{e^*}\left(\frac{X_1^*}{e_1^*}\frac{\partial e_1}{\partial X_1}\right)\left(\frac{\omega_1}{X_1^*}\frac{\partial X_1}{\partial \omega_1}\right)\left(\frac{\theta_1}{\omega_1}\frac{\partial \omega_1}{\partial \theta_1}\right)$$
$$+ \frac{e_2^*}{e^*}\left(\frac{X_2^*}{e_2^*}\frac{\partial e_2}{\partial X_2}\right)\left(\frac{\omega_1}{X_2^*}\frac{\partial X_2}{\partial \omega_1}\right)\left(\frac{\theta_1}{\omega_1}\frac{\partial \omega_1}{\partial \theta_1}\right). \qquad (\mathrm{A.2})$$

From (11), the elasticity of energy demand for service i, with respect to the given demand for service i, $\eta_{X_i}^{e_i} = \frac{X_i}{e_i^*}\frac{\partial e_i^*}{\partial X_i}$, is 1. Letting the portion of energy demand by service *i* be $s_i = e_i/e$ and the elasticities be $\eta_{Z_j}^{Y_i} = \frac{Z_j}{Y_i^*}\frac{\partial Y_i^*}{\partial Z_j}$, we obtain (16).

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