An End-Use Energy Demand Monitoring Project for Estimating the Potential of Energy Savings in the Residential Sector

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ABSTRACT

This paper describes an extensive monitoring project which collected end-use electric power, city gas consumption and ambient and room temperature measuring at thirty minute intervals over one year for 40 residential houses in a newly developed town in the suburb of Kyoto and Nara. The primary purpose of this project is to estimate the potential for energy saving and to find effective ways to achieve energy saving in the residential sector in Japan. Better understanding of the nature of energy demand in residential houses is essential in order to identify savings opportunities at the end use level.

The monitoring system used was completely automatic, and the data for the period from Oct. 1998 to Nov. 1999 have been acquired successfully. The measured data were separated into end-use purposes such as the demand for space cooling and heating, hot water and cooking. Daily load curves for each end-use have been estimated from the measured data.

In this paper, the project will be described in detail, and the present state of end-use energy demand in the relatively new typical residential houses in Kansai region of Japan, will be described.

Introduction

Energy demand in the residential and commercial sectors of Japan is increasing steadily at the annual rate of about 2.9% during the last 25 years after the oil crisis in 1973, while the demand in the industrial sector has been fairly constant. As a result, the share of energy demand in the residential and commercial sectors is now 26% of the total final energy demand. CO_2 emissions from these sectors amounts to 85 million carbon tons which is about 30% of the total CO_2 emission in Japan. Substantial energy saving for the residential and commercial sectors will be necessary for reducing future CO_2 emission. Therefore understanding the nature of residential energy demand by end-use purposes such as space cooling and heating, hot water, cooking, etc. is vitally important to find effective ways for achieving energy savings in this sector.

The authors are carrying out an extensive monitoring project with the financial aid from the Japan Society for Promotion of Science (JSPS) in which electricity and city gas consumption are measured simultaneously for 40 residential houses in a newly developed town located in the suburb of Kyoto. The immediate goal of this project is i) to separate electricity and city gas demand into end-use purposes such as space cooling and heating, water heating, cooking, etc. and ii) to obtain daily load curve for each end-use purpose.

Similar monitoring projects have been reported in the literature. The ELCAP is the most ambitious project in which over 400 residential houses in the Pacific Northwest were monitored over the period of 5 years [Pratt, 1993]. ADEME of France started monitoring in

1995 end-use demand for 100 houses by using 10 sets of end-use monitoring system [Lebot, 1995]. More recently, BRANZ in New Zealand have started a similar project in which the demand at the whole house level is to be measured for 500 houses; 55 of them are to be equipped with end-use monitoring system [Pollard, 1999]. In Japan, a couple of projects were carried out in the last ten years by a utility company and by the Energy Conservation Center, Japan. The former project measured electric power consumption at the whole house level for 1,200 houses, but gas consumption was not measured. The latter project monitored end-use demand for 34 houses, however the number of appliances where energy use was measured was limited. For both cases, data are not publicly available for analysis. In this context, monitoring project of this scale has scarcely been pursued publicly in Japan, and the acquired data will be valuable for clarifying the nature of end-use energy demand in the residential sector.

In this paper, the present state of end-use energy demand in the relatively new typical residential houses in Kansai region of Japan, will be explored. Possible causes of the variability in energy consumption from one monitored house to another will be discussed from the perspective of the major appliances as well as from so-called life-style of the occupants in these houses.

General Description of the Monitoring Project

Monitoring System

The monitoring is being carried out automatically in the way illustrated in Fig. 1.

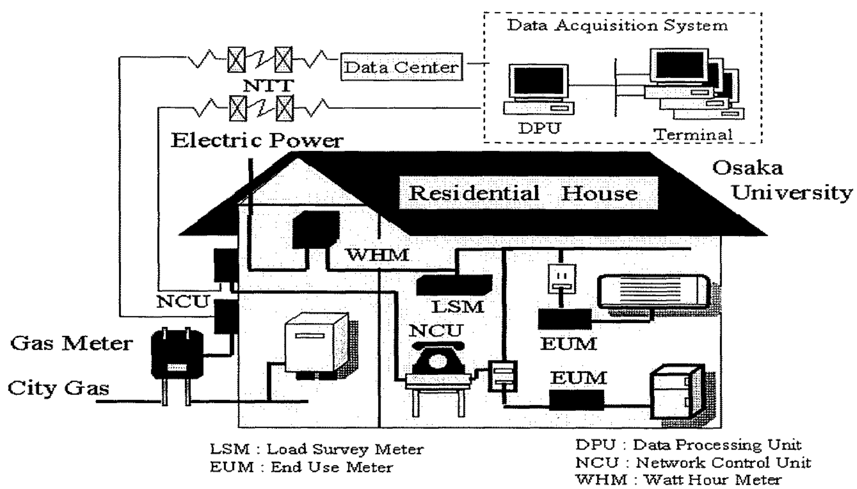


Fig. 1 Data acquisition system

For electric power, the Load Survey Meter (LSM) measures the active and reactive power for the whole house, the End-Use Meter (EUM) measures the active power for each of the home appliances that consume electric power, e.g., refrigerator, TV, etc. The LSM is installed on the customer side of the watt hour meter near the breaker. The EUM is installed between the appliance and the outlet. The measured data are accumulated in the LSM and EUM, and then these data are sent to the Network Control Unit (NCU) through the distribution lines in the house. These data are then collected by the data acquisition center located at Osaka

University through the telephone line by utilizing the 'No Ringing Service' (telephone does not ring when it is called through this service) provided by NTT. The maximum number of End-Use Meters that can be installed in a single house is 8 in the present monitoring system.

For city gas, a microcomputer based meter with communication capability is set up for each house and the data are transferred to the data station in the same way as in the case of electric power measurement. For both electric power and city gas, energy consumption for every 30 minutes intervals is measured. Outdoor and room temperature are measured by a number of data loggers. The loggers can store data for about 80 days when instantaneous temperature is measured every 30 minutes.

The major end-use purposes of city gas in Japan are cooking, hot water and space heating by various appliances such as fan heater and floor heating system. The present monitoring system measures the gas demand at the whole house only, that is, it does not directly measure the city gas consumption for each end-use purpose. However, since most of the gas appliances consume electric power because they are equipped with electric fan motors and controllers, electric power consumption of city gas appliances has also been measured to help determine when the gas appliances are operating.

The first period of the monitoring project was from Oct. 1998 until Nov. 1999. Some of these houses will continue to be monitored for another one year. This will give us opportunity to measure the effects of various energy conservation technologies and activities directly.

Selection of Households to be Monitored

The town selected for the monitoring site is called the "Kansai science, technology and cultural city", and the residents have relatively strong interests in science and technology. A questionnaire was distributed to 1,700 residential houses in the town with the help of the local administration in order to identify cooperative households.

188 households responded positively to our request to meter their homes energy use. After scheduling interviews in more than 50 houses, 40 households have finally agreed to participate in the monitoring. Households were selected using the following criteria.

-Variability in the structure of energy systems
-Large variability in energy consumption
-Family structure should be standard (e.g., 2 adults and 2 children)
-Size of houses (floor area) should be standard (around 120m^2)
-Inclusion of both highly insulated houses and ordinary houses.

The list of monitored households is given in Table 1. The characteristics of the 40 houses are not necessarily representative of Japanese households in general. However, the town was developed about 10 years ago and most of the monitored houses were built in the last five years or so. These monitored houses represent relatively new type (in various aspects such as floor area, number of rooms, many of which pre-fabricated by large manufacturers at a similar price) of houses in Kansai region of Japan.

Separation of Energy Demand into End-Use Purposes

Energy end-use purposes can be categorized in various ways. Here, the following 6 end-use purposes are considered: 1) space heating and cooling, 2) hot water, 3) cooking, 4) television, 5) refrigerator and 6) clothes washer. The last three are the most predominant

Table 1 List of monitored households

Space Heating & Cooling Method	Electric Appliances Only	Electric & Gas Appliances	Electric & Gas Air-Conditioners †	Electric & Oil Appliances
Highly Insulated Houses*	M&W&2ch(165)	M&W&3ch(131) S FH	M&W&2ch(122) S	M&W&2ch(142) S
	M&W&2ch(132)	M&W&2ch(121) S		M&W&2ch(130)
	M&W&2ch(122)	M&W&2ch(100) S		M&W&2ch(122)
Ordinary Houses	M&W&1ch(140)	M&W&2ch(143)	M&W&1ch(154)	M&W&1ch(230)
	M&W&2ch(136)	M&W&2ch(134)	M&W&3ch(150) FH	M&W&2ch(145) S FH
	M&W&3ch(135)	M&W&2ch(133) S	M&W&2ch(130)	M&W&2ch(142)
	M&W&3ch(130)	M&W&2ch(125)	M&W&2ch(130) FH	M&W&2ch(140)
	M&W&2ch(120)	M&W&2ch(123)	M&W&3ch(123) FH	M&W&3ch(130) S
	M&W(135) **	M&W&2ch(120)	M&W&3ch(120) S	M&W&2ch(122) FH
		M&W(124) S	M&W&2ch&GM(120) S	M&W&2ch(120) FH
			M&W(140)	M&W&2ch(116)
				M&W&1ch(116) S
Total	9	10	9	12

M&W&2ch&GP implies a household with 2 adults, 2 children and 1 grandparent. ( ):Total floor area [m²]
S: House with solar water heating system FH: House with floor heating
*Claimed by house owner **House without air-conditioner
† Combined systems using electric power for cooling and gas for space heating

appliances consuming a significant fraction of total electric power per household. Other energy end-use purposes including lighting appliances are included in "others". A number of home appliances that are frequently used are listed and categorized into these end-use purposes as shown in Fig. 2. A more detailed description of the traditional and contemporary home appliances in Japan (e.g. *kotatsu*) can be found in previous reports [Fujii,1992]. Fig. 2 may be considered as a general structure of energy system in residential sector.

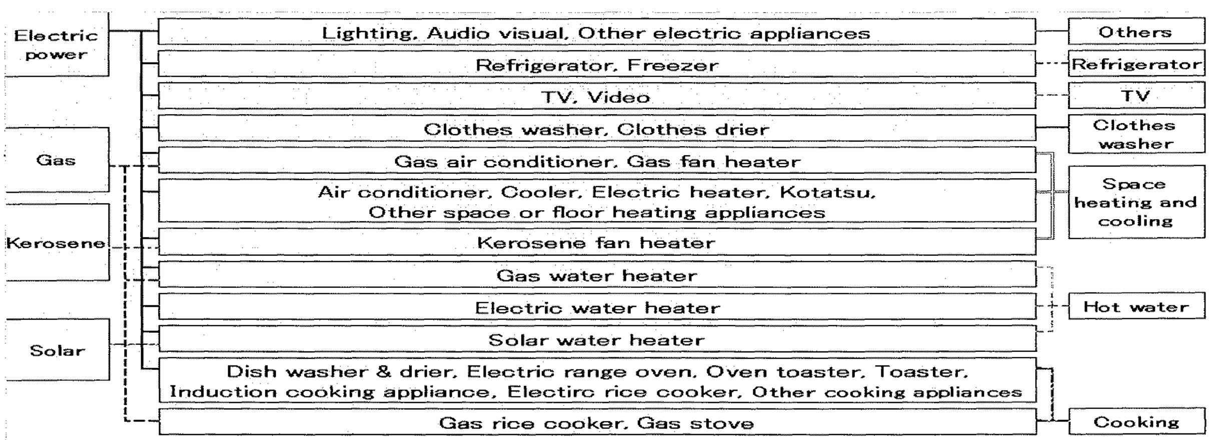


Fig. 2 Categorization of end-use purposes

Separation of Electric Power Demand

The number of EUM's that can be placed in a single house was limited to 8 and some of the electric appliances are used only in summer or in winter. Therefore, the measurement schedule must be carefully planned so that the electric power demand of every appliance can be eventually monitored at least for a month or so.

An example of the measurement schedule at a typical house is illustrated in Fig. 3. In this example, power consumption of the refrigerator was measured only for the period from May to September although the refrigerator is actually used throughout the year. Our primary purpose of monitoring is to separate the total demand (measured by LSM) into each end-use demand and also to obtain a daily load profile that varies over seasons for each end-use purpose. Therefore, it is necessary to estimate from the measured data the power consumption of the refrigerator during the period when no measurement data was collected, say in Feb.

In order to make this estimate, the seasonal variation of power consumption of a particular appliance must be taken into account. For example, the power consumption of refrigerators may depend on ambient or room temperature. In order to clarify the dependence of the refrigerator on temperature, power consumption of several refrigerators must be measured throughout the year. Thus, these schedules have been carefully designed so that at least several appliances in the same category are to be measured throughout the monitoring period.

After one year of measurement, it became clear that power consumption of cooking appliances, television and washing machine do not vary much over seasons. Therefore, the power consumption rate over the period of no measurement was assumed to be equal to the measured data. For refrigerators, power consumption was related to outdoor temperature (daily average) by a second order polynomial equation with reasonable accuracy.

<table>
<tr><th rowspan="2"></th><th rowspan="2">Voltage</th><th colspan="3">1998</th><th colspan="11">1999</th></tr>
<tr><th>10</th><th>11</th><th>12</th><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th><th>8</th><th>9</th><th>10</th><th>11</th></tr>
<tr><td>EUM 1</td><td>100V</td><td colspan="14">Gas Water Heater</td></tr>
<tr><td>EUM 2</td><td>100V</td><td>Toaster</td><td colspan="6">Kotatsu</td><td colspan="5">Refrigerator</td><td colspan="2">Electric Range Oven</td></tr>
<tr><td>EUM 3</td><td>100V</td><td>TV1</td><td colspan="6">Electric Heater1</td><td colspan="7">TV1</td></tr>
<tr><td>EUM 4</td><td>100V</td><td colspan="14">Gas Air Conditioner</td></tr>
<tr><td>EUM 5</td><td>200V</td><td colspan="14">Air Conditioner 1</td></tr>
<tr><td>EUM 6</td><td>100V</td><td colspan="14">Air Conditioner 2</td></tr>
<tr><td>EUM 7</td><td>100V</td><td>TV2</td><td colspan="6">Electric Heater2</td><td colspan="5">TV2</td><td colspan="2">Clothes Washer</td></tr>
<tr><td>EUM 8</td><td>100V</td><td colspan="14">Solar Water Heater</td></tr>
</table>

Fig. 3 Example of end-use meter measurement schedule

Separation of City Gas Demand

For city gas demand, only the total gas consumption at the whole house level has been measured and therefore it is necessary to separate it into its end-use purposes, i.e., cooking, hot water and space heating. A method for disaggregation has been proposed by Yamagami [Yamagami, 1996]. However, this method is not applicable to our project where the consumption data are accumulated over 30 minutes.

In an effort to separate the total demand into these end-use purposes, electric power consumption of gas water heater and that of gas fan heater were monitored. The former is the most popular water heater in Japanese houses and it is equipped with small induction motor used for cooling the heat exchanger. The latter is a convenient, inexpensive space heating appliance using city gas and it is also equipped with small induction motor in order to push the heated air into the room. Thus, both appliances consume considerable electric power when they are in operation. However, since the power consumption over 30 minutes intervals is measured, information essential for separation is lost in the monitored data. Thus, it is not always easy to relate the power consumption of gas appliance to its gas consumption directly.

A better way of utilizing these power consumption data was to identify the period of time when a particular appliance is *not* in operation. Many of the homes monitored for this project have only two natural gas appliance in operation; cooking and water heating. When this is the case, gas demand for cooking can be determined for any period of the day when the gas water heater is not in operation. This is accomplished by using the electric fan activity connected to the water heater as a proxy for water heater operation. When the gas heater is not operating, any gas usage from the total house meter can be assumed to be related to cooking. This process allows for a reasonably accurate daily gas consumption profile to be developed.

For those homes equipped with space heating gas appliances, the average daily patterns of cooking and water heating are determined first for the seasons when space heating appliances are not in use. Space heating is not necessary except in winter in Kansai region. Then, by assuming that the monthly variations of the gas demand for cooking and water heating are similar to those homes without gas heating appliances, the gas demand for space heating can also be determined by subtracting the demand for cooking and water heating from the total gas demand.

Estimation of Kerosene Demand

Kerosene consumption is not directly measured, but a household member was asked to report the amount of kerosene purchased every month. Kerosene is used for space heating only, so it is not necessary to separate into end-use purposes. However, an estimate of the consumption for every 30 minutes is needed in order to obtain the daily demand profile. Here, it is assumed that the total power consumption of the kerosene heater over the entire winter is linearly related to its total kerosene consumption. From the amount of purchased kerosene and the total power consumption of the appliance, a constant can be calculated for every house. Kerosene consumption over 30 minutes is then estimated by multiplying the power consumption by the constant.

The Present State of Energy Demand

In this section, the state of energy demand in the monitored households is described based on the results of measurement.

The Database

Figure 4 shows the daily electric power and gas consumption averaged over 23 households that are not equipped with a solar water heater. Daily temperature is the average outdoor temperature over a day measured at the two elementary schools in the town. The city gas consumption data for late April to early May is missing in Fig. 4 because of a failure in the data acquisition system. Figure 4 provides an overview of the data acquired by the monitoring project and also shows how the temperature changed over the year. The figure also illustrates how the seasonal variation of gas consumption is more significant than electric power, due to the fact that city gas appliances are used for space heating purpose in many houses.

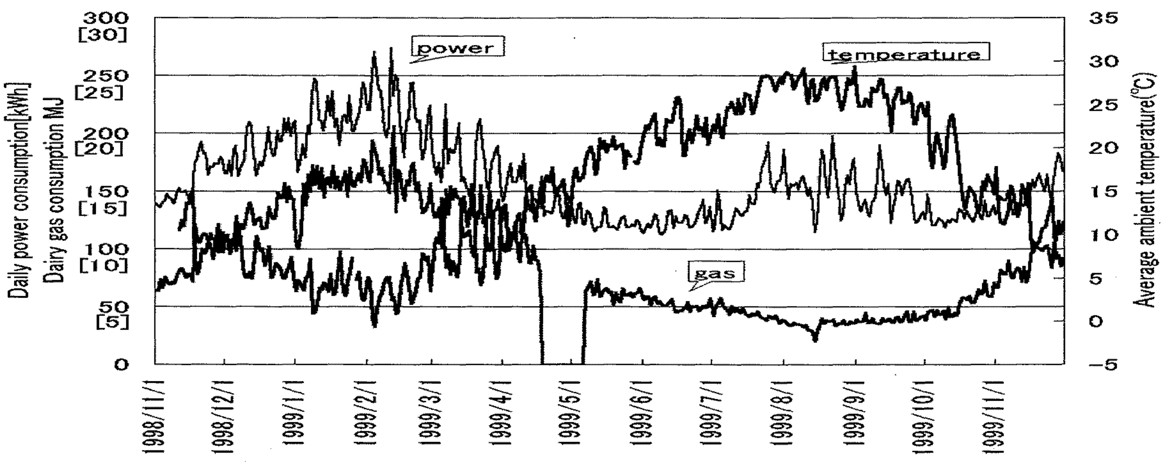


Fig. 4 Overview of the acquired data: Daily energy consumption per household (averaged over 23 households) and outdoor temperature

Annual Consumption per Household

The distribution of the annual total energy consumption for each of the 35 households is shown in Fig. 5a) and b). Figure 5a) represents annual total energy consumption in MWh (secondary energy) by energy source and Fig. 5b) represents annual total energy consumption in GJ (primary energy: converted by 1kWh=10.3MJ) by end-use. There is about 2.8 times difference between the household with the largest consumption and the one with the least consumption, and the difference in consumption for each end-use is quite significant. The average of annual total primary energy consumption of these 35 households is 88GJ, which is 17% larger than the average value of 75GJ (in 1997) over the entire Kansai Region.

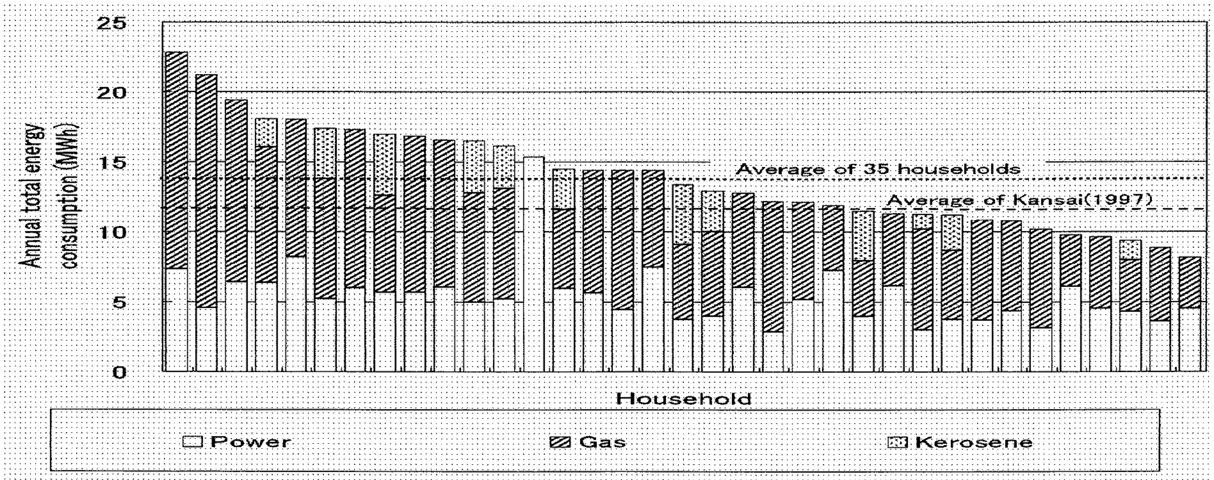
Seasonal Variation

Figures 6a) and b) represent seasonal variation of power consumption and gas consumption by end-use, respectively. The end-use purposes expressed in these figures are the same as in Fig. 2.

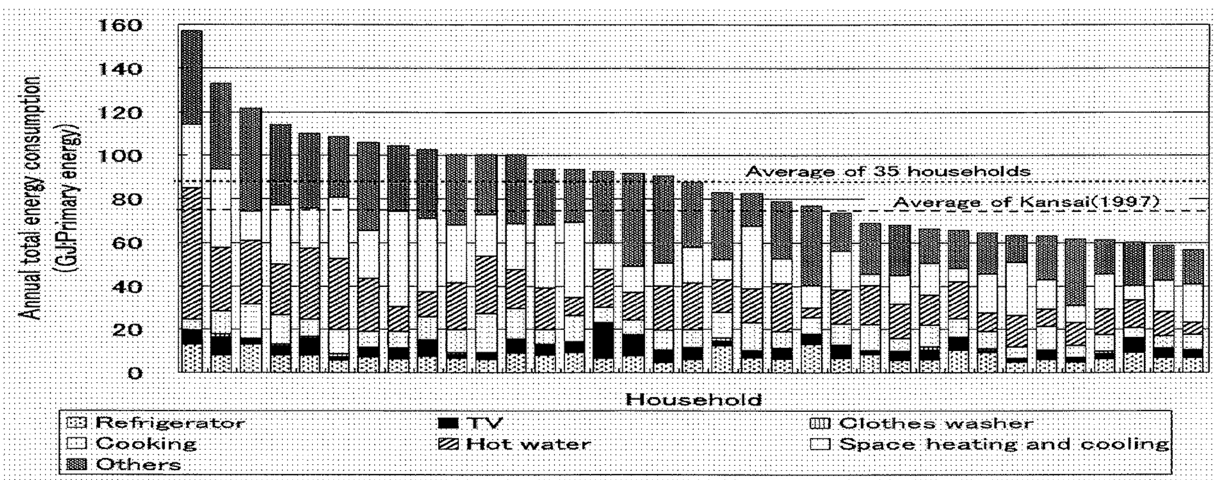
Seasonal variation is significant in the demand for space heating and cooling, hot water, cooking, and refrigerator. In Fig. 6a), power consumption per household is larger in winter than in summer. This is due to the penetration of air-conditioners that can be switched easily from space cooling system in summer to space heating system in winter. Many houses use these heat pump systems [Fujii, 1992] and this contributes to the increase of power consumption during wintertime. Seasonal variation in the gas consumption for hot water and space heating is shown in Fig. 6b).

Daily Load Curves

Figures 7a) and b) represent the daily load curves for electric power and gas, respectively,

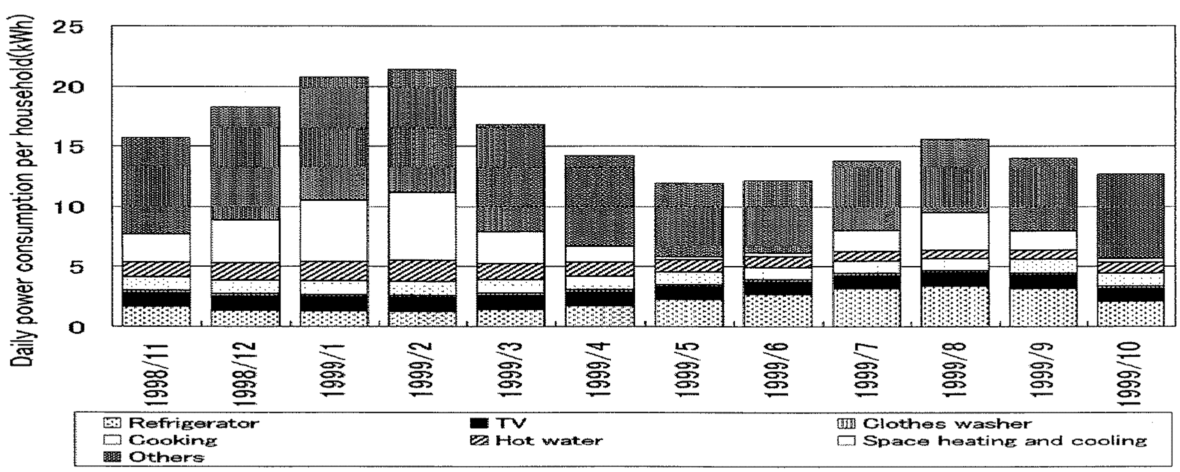


a) Total energy consumption by energy source (secondary energy)



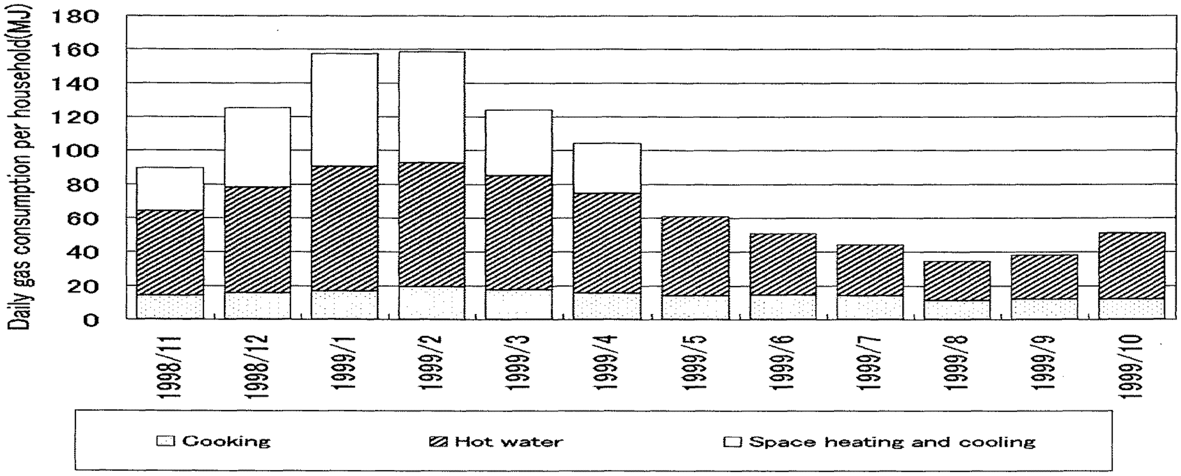
b) Total energy consumption by end-use (primary energy)

Fig. 5 Annual energy consumption per household

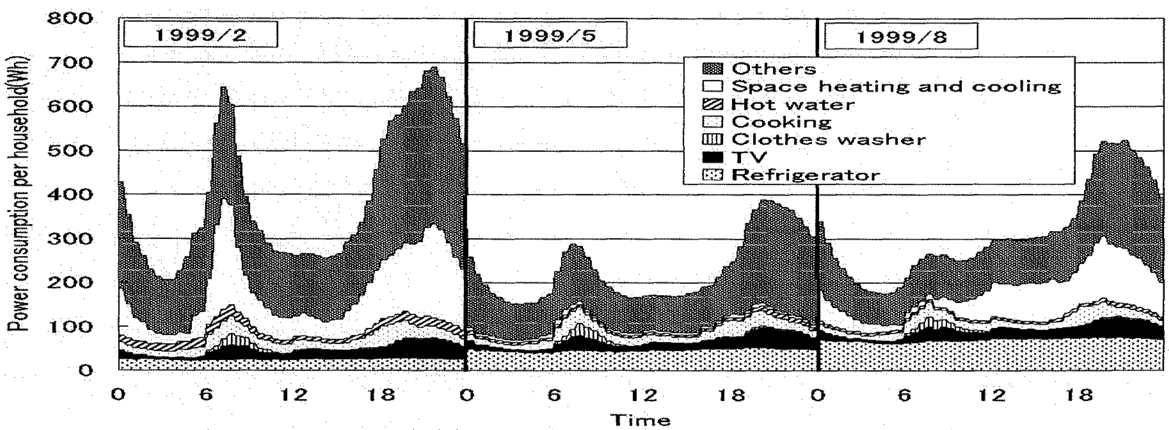


a) Power consumption by end-use (weekdays; averaged over 23 households)

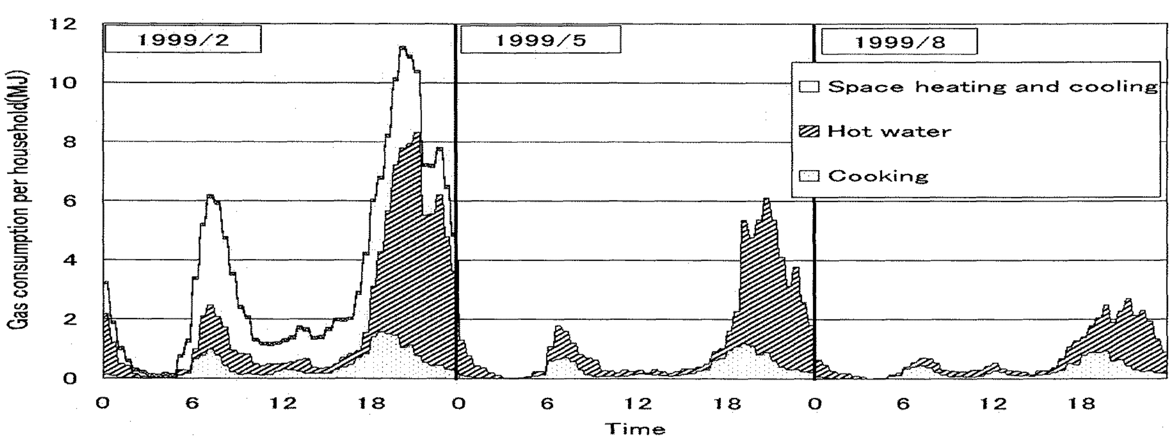
Fig. 6 Seasonal variation of daily electric power and gas consumption per household



b) Gas consumption by end-use (weekdays; averaged over 23 households)
Fig. 6 Seasonal variation of daily electric power and gas consumption per household



a) End-use load curves for electric power (weekdays; averaged over 22 households)



b) End-use load curves for gas (weekdays; averaged over 22 households)
Fig. 7 Daily load curves for electric power and gas

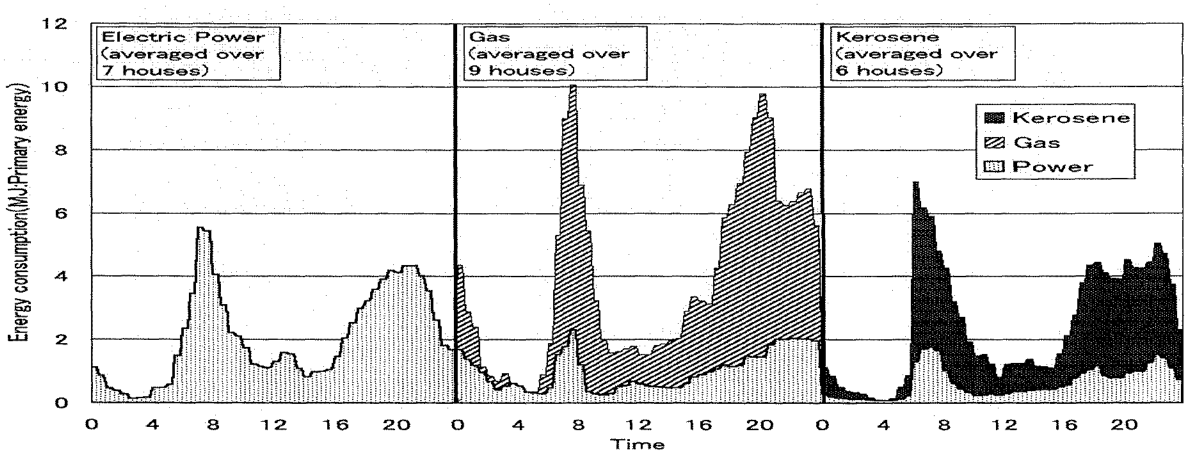
for different seasons. Here the household equipped with electric water heater is excluded from the former sample of 23 houses. The electric water heater is designed to take advantage of using inexpensive nighttime electricity, and its load curve is completely different. Graphs labeled 1999/2, 1999/5, and 1999/8 express typical load curves for winter, spring or autumn, and summer day, respectively. In Fig. 7a) and b), the sharp rise in the winter morning use is shown to be mainly due to space heating. On the other hand, the peak of gas consumption during the night is due to the hot water heater use rather than space heating and cooling. These daily load curves are closely related to the activities (or life styles) of the household members.

Preliminary Analysis of the Differences between Household Consumption

Difference in Energy Demand by Energy System Structure

The three major categories described in Table 1 are mainly differentiated by space heating method. That is, category 1) includes home where space heating is by electric appliances only, 2) includes homes with both electric and gas appliances, and 3) includes home heated by both electric and kerosene appliances. Load curves for space heating are shown in Fig. 8. The figure shows that the energy consumption for space heating is the least in category 1) and the largest in category 2). Since the number of samples in each category is very small, the results cannot be generalized. However, it can be speculated that relatively high COP or efficiency in electric heat pump air-conditioners may have contributed to the reduction of primary energy consumption in category 1) relative to gas or kerosene space heaters.

Fig. 8 Load curves for space heating (by energy system structure)



Comparison between Two Houses

It is interesting to investigate the cause of the differences between those households with large energy use and those with less energy use. The possible causes of the difference in energy use between households are: the performance/efficiency of appliances, contributions of solar water heater to reduce primary energy use, the degree of insulation, energy system structure, and occupants patterns or schedules for using appliances.

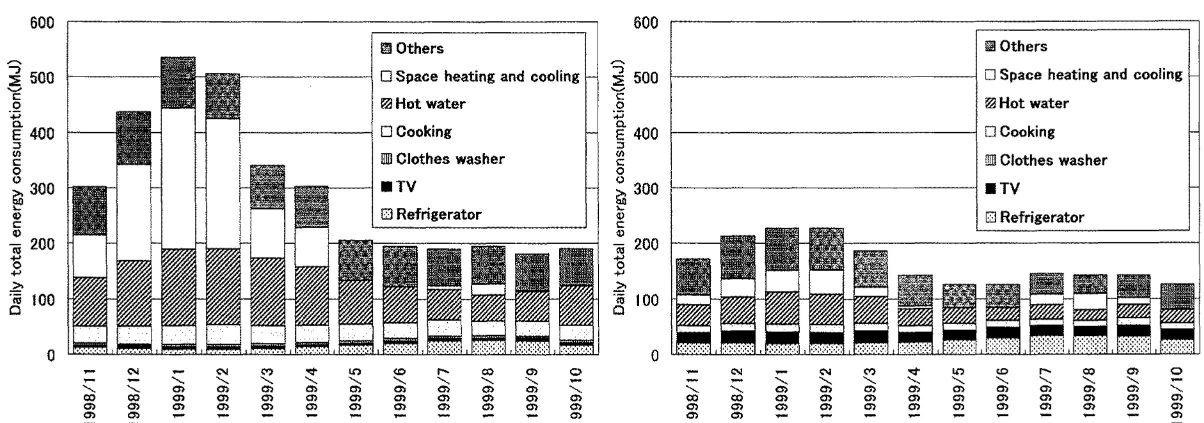
The energy usage at the end use level for two houses described in Table 2 are compared with each other. Household A and B are both considered standard, and the major differences are in the age of children and in the energy systems as shown in Table 2. Figure 9 shows seasonal variation of total primary energy consumption by end-use for both households. The major difference is clearly in the demand for hot water and space heating.

Daily load curves for hot water and space heating for Household A and B in February are shown in Fig. 10. By investigating the activities of household members in these two houses, it became clear that the timing and frequency of taking baths caused the difference in the demand for hot water. Re-heating and keeping the temperature of hot water at certain level was a common practice in Household A but not in B. Therefore the energy consumption of water heater became much larger for this home than B as shown in Fig. 10a).

Figure 10b) shows load curves for space heating. The space heating load for Household A was larger than in B throughout the day. The average temperature of living room in February was 22.9 degree Celsius in Household A and 21.2 in B when the heating appliances for the living room were used continuously for one hour or more. The major heating appliance in the living room of Household A was gas fan heater shown in Table 2 requiring frequent ventilation. In addition, some of the heating appliances in Household A were used in the rooms other than the living room. On the other hand only the heat pump air-conditioner was used in the living room of B. This observation suggests that Household A has more potential for energy savings than B, but more analysis is needed to confirm it.

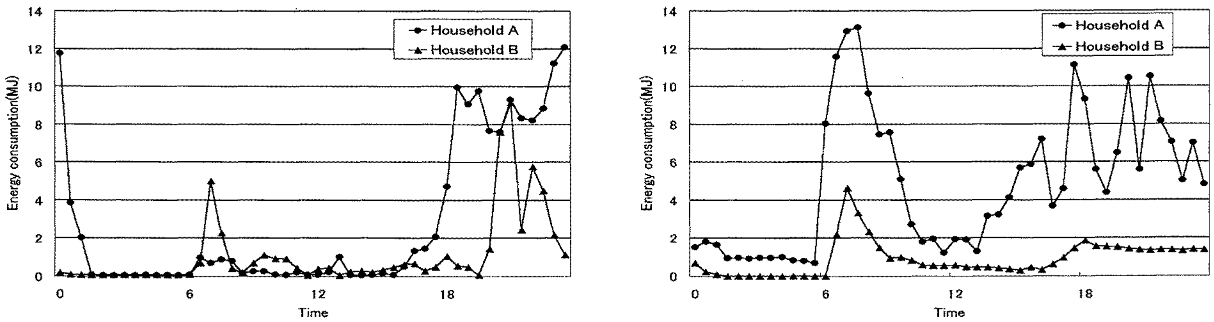
Table 2 Features of Household A and B

	Household A	Household B
Member of household	2 adults 2 Elementary school students	2 adults 1 Junior high and 1 High school students
Space Heating & Cooling Method	Air−conditioner Gas fan heater Electric heater Electric carpet	Air−conditioner Electric heater
Annual total primary energy consumption	109GJ	60GJ
Annual power / gas consumption	4480kWh / 63GJ	4500kWh / 14GJ
Floor area / Insulation level	123㎡ / Ordinary	120㎡ / Ordinary



a) Household A b) Household B

Fig. 9 Comparison between Household A and B: Seasonal variation of energy consumption



a) Hot water b) Space heating
Fig. 10 Comparison between Household A and B: Daily load curves averaged over weekdays of February.

Concluding Remarks

The monitoring project in Kansai Region of Japan was successful in disaggregating whole house energy measurements to the end use level. Seasonal variations and the daily load curve for each end-use demand category were also obtained. Preliminary analysis has suggested that the potential of energy savings is still large in this newly developed town.

The obtained data are valuable because there is no well-established database describing the daily energy usage at the end use level for the domestic sector of Japan. There is considerable of room for future study in order to understand the nature of energy consumption in residential houses in Japan and identifying opportunities to reduce energy use by making use of this measured data.

Acknowledgments

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