A Two Year Measurement of Energy Consumption and Indoor Temperature of 13 Houses in a Cold Climatic Region of Japan

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Abstract
The energy consumption and indoor temperature of 13 housing units sited in the northern region of Honshu Island, Japan were investigated for a full two years from Dec. 2002 to Nov. 2004. Five of the houses were installed with all-electric equipment. The annual and daily energy consumption profiles of two typical houses were analyzed, and the annual energy consumption per house was found to range from 40GJ/year to 120GJ/year. The difference of energy consumption between the two years was very small, while in some houses, energy consumption during the second year decreased due to a rise in energy saving awareness. The results indicated that the characteristics of energy consumption were not only greatly influenced by regional climate but also by the use of household equipment and lifestyle. Finally, the relationship between energy consumption for space heating and indoor temperature is discussed.

Keywords: energy consumption; lifestyles; indoor thermal environment; house; field measurement

1. Introduction
In line with the recognition that a sustainable global environment is the most important environmental issue, global warming must also be handled urgently. As a result of improved living standards throughout the world, energy consumption by households is also growing. In Japan, the average annual growth rate of residential energy consumption was 4.3% from 1965 to 2003 (Handbook 2005). For this reason, it is important to take immediate action to minimize energy consumption by the housing sector.

The objective of this study is to understand the current condition of energy consumption and thermal environment in the daily life of households located in the northern region of Honshu Island, Japan.

Many researches on housing energy consumption in Japan have been performed, and can generally be classified into two; nation-wide and regional. The nationwide investigations include those by Ojima and Masuda (1980, 1981) who investigated the energy consumption of 1,200 houses in various cities of all prefectures based on an expenditure survey of households. Sawachi, Bogaki et al. (1994) conducted a questionnaire survey of household energy consumption in eight cities and analyzed the influential factors concerning energy consumption according to end use. Ishida (1997) investigated the energy consumption trends of detached houses in 13 cities and analyzed the contributing factors. Miura et al. (1998, 2002) estimated the household energy consumption for all prefectures of Japan and established clear regional characteristics by using annual public statistical data. Hasegawa and Inoue (2004) conducted an internet questionnaire survey throughout the country to investigate relationships between energy consumption, household characteristics and the occupants' awareness.

On the other hand, the regional investigations include Hamada, Nakamura et al. (2001) who measured the energy consumption of various appliances in detail for 11 households in Hokkaido Prefecture. Hasegawa, Yoshino et al. (2002) investigated the indoor environment and energy consumption for three hundred well-insulated and airtight houses in the Tohoku region. Adachi, Akabayashi et al. (1994) investigated the lifestyle and energy consumption of hundreds of households in Niigata Prefecture. Fukushima, Urano et al. (1995) carried out a questionnaire survey of 1,000-2,000 houses in Kyushu Prefecture.

In this study, detailed measurements of energy consumption for each end use as well as indoor temperature and humidity were carried out over a period of two years. Part of the results of this project were reported in other studies (Yamagishi et al. 2005, Murakami et al. 2005, Yoshino et al. 2004).
2. Measurement

2.1 Outline of the houses

In this study, 13 houses located in the northern region of Honshu Island, Japan were investigated. The outline of these houses is shown in Table 1. Nine detached houses and four apartments in Miyagi, Iwate, Akita and Fukushima prefectures were involved in this investigation. All the detached-type houses are made of wood and the four apartments are built by SRC (steel reinforced concrete) or RC (reinforced concrete). The floor areas of the detached houses and apartments are 110~180m² and 70~80m², respectively. When these houses were newly constructed, they were well insulated and airtight. The value of heating transmission rate was calculated based on the design plans and components. The value of equivalent leakage areas per floor area (equivalent leakage area) was measured by the fan pressurization method. In addition, the main energy sources were kerosene, electricity and gas. The five houses investigated used only electricity. In these houses, electric thermal storage heating equipment was installed.

2.2 Items of measurement

The major items investigated in the measurement are given in Table 2. These include energy consumption, thermal environment, capacity of electrical appliances and the occupants’ lifestyle, etc. The measurement intervals for electricity consumption, gas consumption, kerosene consumption, and temperature were 1 minute, 5 minutes, 5 minutes, and 15 minutes.

2.3 Categories of energy consumption

End use of energy consumption was classified into six categories, i.e. space heating/cooling, hot water supply, kitchen, audio visual/information, healthcare, lighting and others. The category of “lighting and others” means the energy consumed for lighting and unidentified usage. Receipts for electricity, gas, and kerosene consumption were used to compensate for missing data in situations where the measuring instruments were not functioning.

3. Comparison of the Energy Consumption of Two Typical Houses

3.1 Outline of the two houses under investigation

The energy consumption of house D01 that used electricity and kerosene as sources of energy, is compared with house D07 that used only electricity. The energy consumptions of houses D01 and D07 were the largest among the all-electrified houses and non all-electrified houses. These two houses were located in Sendai and Morioka cities. The number of occupants in D01 and D07 were 5 and 4, respectively.

3.2 Two-year profile of daily energy consumption

Profiles of daily amount of energy consumption and daily mean temperature of these two houses over a two-year period, from Dec. 2002 to Nov. 2004, are shown in Fig.1. In house D01, the living room temperature changes in a range of 21°C to 29°C during the measured period, while that of house D07 is between 18°C to 29°C. Energy consumption in both

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Table 1. Description of Houses Investigated (Survey Period: from Nov. 2002 to Nov. 2004)

| No. | Location | Number of occupants | Floor area (m²) | Heat loss coefficient (W/m²K) | Equivalent leakage area (cm³/m²) | Construction | Energy sources by usage |
|-----|----------|---------------------|-----------------|-------------------------------|----------------------------------|--------------|------------------------|
|     |          |                     |                 |                               |                                  |              | Space heating | Space cooling | Hot water supply | Kitchen |
| D01 | Miyagi   | 5                   | 150.9           | 1.88                          | 0.85                             | Wood         | Kern¹⁺, Kern²⁺, Kern³⁺, Kern⁴⁺, Kern⁵⁺, Kern⁶⁺ |
| D02 | Miyagi   | 4                   | 153.4           | 1.79                          | 0.93                             | Wood         | Kern¹⁺, Kern²⁺, Kern³⁺, Kern⁴⁺, Kern⁵⁺, Kern⁶⁺ |
| D03 | Miyagi   | 3                   | 115.9           | 1.72                          | 0.76                             | Wood         | Kern¹⁺, Kern²⁺, Kern³⁺, Kern⁴⁺, Kern⁵⁺, Kern⁶⁺ |
| D04 | Akita    | 3                   | 106.3           | 1.77                          | 0.87                             | Wood         | Kern¹⁺, Kern²⁺, Kern³⁺, Kern⁴⁺, Kern⁵⁺, Kern⁶⁺ |
| D05 | Akita    | 3                   | 141.6           | 1.79                          | 0.77                             | Wood         | Kern¹⁺, Kern²⁺, Kern³⁺, Kern⁴⁺, Kern⁵⁺, Kern⁶⁺ |
| D06 | Akita    | 4                   | 160.6           | 1.84                          | 2.20                             | Wood         | Kern¹⁺, Kern²⁺, Kern³⁺, Kern⁴⁺, Kern⁵⁺, Kern⁶⁺ |
| D07 | Iwate    | 4                   | 140.0           | 1.91                          | 0.70                             | Wood         | Kern¹⁺, Kern²⁺, Kern³⁺, Kern⁴⁺, Kern⁵⁺, Kern⁶⁺ |
| D08 | Iwate    | 4                   | 178.0²⁺         | 1.16                          | 0.40                             | Wood         | Kern¹⁺, Kern²⁺, Kern³⁺, Kern⁴⁺, Kern⁵⁺, Kern⁶⁺ |
| D09 | Iwate    | 2                   | 149.9           | 1.46                          | 0.95                             | Wood         | Kern¹⁺, Kern²⁺, Kern³⁺, Kern⁴⁺, Kern⁵⁺, Kern⁶⁺ |
| A01 | Fukushima| 3                   | 72.3            | 2.47                          | 1.74                             | SRC          | Elec.²⁺, Elec.³⁺, Elec.⁴⁺, Elec.⁵⁺, Elec.⁶⁺, Gas |
| A02 | Fukushima| 3                   | 78.0            | —                             | 0.47                             | RC           | Elec.²⁺, Elec.³⁺, Elec.⁴⁺, Elec.⁵⁺, Elec.⁶⁺, Gas |
| A03 | Akita    | 4                   | 78.3            | 1.68                          | 1.52                             | RC           | Kern³⁺, Kern⁴⁺, Kern⁵⁺, Kern⁶⁺, Gas |
| A04 | Iwate    | 2                   | 80.0            | —                             | 0.71                             | RC           | Kern³⁺, Kern⁴⁺, Kern⁵⁺, Kern⁶⁺, Gas |

Notes: Kern: Kerosene Elec.: Electricity ¹⁺: It includes 58m² of underground spaces.
Space heating equipment: ²⁺: hot water heating panel ³⁺: electric thermal storage heating equipment ⁴⁺: portable kerosene heater ⁵⁺: air conditioner

Table 2. Measurement Items

| Investigated                              | Measurement                              |
|-------------------------------------------|------------------------------------------|
| Electricity                               | Home energy consumption recording system with interval of 1 minute |
| Gas                                       | Digital camera signal data logger with interval of 5 minutes |
| Kerosene                                  | Fine flow rate fuel oil meter with interval of 5 minutes |
| Temperature & relative humidity           | Small sensor and data loggers with interval of 15 minutes |
| Questionnaire                             | Life-style, energy-saving consciousness, annul income, usage frequency and capacity of equipment |
| Interview                                 | Family structure |

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houses increased in the winter due to space heating, but it is noted that the energy consumption of house D01 is about double that of house D07. The difference is because space heating was used entirely for house D01 but only partially for house D07. Another reason is that the value of heat loss coefficient of house D01 was 1.88 (W/m²/k) while house D07 was only 1.01 (W/m²/k). The energy consumption of kitchen, audio visual/information, and healthcare, lighting and others are almost constant. The annual profiles were similar for both years.

3.3 Energy consumption profile on typical days

The profiles of energy consumption and temperature during three days in winter/summer are shown in Fig.2. The middle day among three days was the coldest/hottest day with the lowest/highest outdoor air temperature during the investigation period. Each diagram of Fig.2. is divided into three sections: the higher section shows the outdoor air and living room temperature, the middle section gives the energy consumption of three uses (space heating/cooling, hot water supply, and others), and the lower section illustrates the energy consumption of the other items (kitchen, audio visual/information, healthcare, and lighting and others). The energy consumption is shown at intervals of 15 minutes.

The coldest day

The temperature of the living room in D01 and D07 is almost constant during the coldest period, at 23°C and 20°C, respectively. This is due to the fact that space heating is used all day in both houses. However, the energy consumption profiles are significantly different between the two houses. As the hot water heating panel was operated for the whole day in house D01, there was no peak energy consumption (except for hot water supply). In house D07, the energy was mainly consumed from 11 p.m.~7 a.m. by the thermal storage heating equipment using nighttime electric power. As shown in the lower section of the diagram in Fig.2., there are several peaks of energy consumption due to cooking activities.

The hottest day

The temperature change in the living room ranged from 27°C to 30°C for house D01 and 25°C to 30°C for house D07. There was no obvious difference in the energy consumption trends of houses D01 and D07, except energy consumption for hot water.

3.4 Correlation between temperature and energy consumption by end use

The correlation between outdoor temperature and energy consumption categorized as space heating/cooling, hot water supply, electric toilet seat and refrigerator is given in Fig.3. All data was the daily average value during the period from Dec. 2002 to Nov. 2004. Fig.3. shows a strong correlation between energy consumption for space heating/cooling and the outdoor temperature. There were some days with no consumption because the house was not occupied during the holidays. On the other hand, the correlation of hot water supply was relatively weak, while the correlation between energy consumption for refrigerator and the outdoor air temperature was strong. The energy consumption became larger when the outdoor air temperature was higher. Energy consumption for the electric toilet seat can be divided into three groups, which seem to have different thermostatic mode settings; the energy consumption was less when it was set to a higher temperature mode, and less at a higher temperature in each operating mode.

Fig.1. Two-year Profile of Daily Energy Consumption and Temperature
Energy Consumption and Temperature of All Investigated Houses

4.1 Annual energy consumption

The annual energy consumptions of thirteen houses are shown in Fig.4., with the statistical reference values from literature (Handbook 2005) for the Tohoku District in Japan. The periods of the first and second years were from Dec. 2002 to Nov. 2003 and from Dec. 2003 to Nov. 2004, respectively. The statistical reference value is the average of 2002. Energy consumption by end use is classified into four categories; space heating, space cooling, hot water supply and others (Fig.4.-a). It is noted that the hot water supply includes gas consumption for cooking in the case of apartments. The category of “others” divided as ventilation, refrigerator, kitchen, audio visual/information, healthcare, lighting and others is shown in Fig.4.-b. Energy consumption for audio visual/information includes consumption for lighting and others in house D05. The statistical reference value is not divided. The total energy consumption per person per square meter is shown in Fig.4.-c.

Difference between houses

As shown in Fig.4.-a, the annual total energy consumption per house varied between 40~120GJ/year. The major energy consuming activities for detached houses and apartments were space heating and hot water supply respectively. The energy consumption in D01 was the largest, which was nearly twice that of the reference value. This house consumed energy largely for space heating because the floor area was large and required more energy to keep the rooms warm. In contrast, the energy consumption of D03 and D04 was about two thirds of the reference value. In these two houses, occupants practised energy saving awareness as revealed by a questionnaire. Fig.4.-b shows the energy consumption of "others", which was used by refrigerator, kitchen, audio visual/information, healthcare, lighting and others. The characteristics of end use were different between houses.

Difference between detached houses and apartments

Fig.4.-a shows the trends of energy consumption according to end use for detached houses and apartments. The percentages of space heating and hot water supply in the case of detached houses were approximately 50% and 20% respectively, and 20% and 50% in the case of apartments. In both cases the energy consumed for space heating and hot water supply was above 70% of the total energy consumption.

Comparison between the first and second year

The results show that energy consumption in the
first year was almost the same as the second year for most houses, except D01 and D06. Based on the questionnaire survey, it was found that the energy saving awareness of the occupants of D01 and D06 became higher in the second year. One example of concrete action for saving energy was in house D01 where the warm water heating system was turned off when the house was unoccupied. In the case of house D06, space heating was used for the entrance, lavatory and toilet in the first year, but was not used for these spaces in the second year.

**Energy consumption per person per square meter**

Fig. 4.-c shows the energy consumption per person per square meter. The values for detached houses were less than those of apartments; approximately 0.12 and 0.23GJ, respectively.

4.2 Indoor and outdoor air temperatures

(1) Winter and summer temperatures

**In winter**

Fig. 5. shows the temperature of outdoor air, living room and bedroom, including the monthly maximum and minimum values, and standard deviations in January, 2003 and 2004. (All data based on 15 minute intervals was compiled).

The outdoor air temperature changed from -5°C to 5°C and the indoor temperature from 10°C to 25°C. The living room temperature was higher than that of the bedroom in almost all houses. In houses D04, A01, A02 and A03, the temperatures of living rooms were high and unstable, while those of bedrooms were low. In these houses, the portable kerosene heaters and air conditioners were intermittently operated. However, in houses D03, D06 and D07, the difference of temperature between living room and bedroom was not significant. In D03, the temperature was low, because space heating was not frequently used due to the high energy saving consciousness of the occupant. In D06 and D07 with hot water heating panels and electric thermal storage heating, respectively, the temperatures were high and stable, the space heating equipment was used all day in all rooms. On the other hand, the temperatures were similar between Jan. 2003 and Jan. 2004 in each house, except D02. In D02, the temperature during Jan. 2004 was not stable compared to the first year, because the house was not occupied at the beginning of Jan. 2004.

**In summer**

The outdoor temperature changed between 20°C and 30°C, while the indoor temperature changed between 22°C and 32°C. The outdoor temperature of the summer of Aug. 2003 was lower compared with that of Aug. 2004. Therefore the living room and bedroom temperatures of almost all houses were lower during Aug. 2003. In the case of houses D04 and D05 during Aug. 2004 the living room temperature was high at approximately 32°C , because the operating time for the air conditioner was short. In house D08, the temperature was kept below 27°C without any cooling equipment. One reason is that the house is well insulated and airtight with a solar shading device. Another reason is that it has underground space.

(2) Correlation between indoor and outdoor air temperature

The correlations of daily mean values between living room, bedroom and outdoor air temperature in three houses are shown in Fig. 6. The three houses are house D01 with the highest daily average temperature of the living room, D03 with the lowest, and A01 with the
most varied indoor temperature in winter. The period of the data is from Dec. 2002 to Nov. 2003. In the case of D01, the living room temperature was relatively stable although the outdoor air temperature was remarkably varied. The energy consumption was the largest of all houses (see Fig.4). In the case of D03, the living room temperature rises with the outdoor air temperature and the correlation was very high, while the energy consumption for space heating/cooling was small. In the case of A01, although the indoor temperature generally depends on the outdoor temperature, when the outdoor air temperature is in the range of from 0°C to 5°C, the living room temperature varies significantly. The energy consumption for space heating of A01 was between that of D01 and D03.

4.3 Energy consumption and indoor-outdoor temperature difference

The energy consumption for space heating in January is calculated by equation (1) based on the heat loss coefficient and indoor, outdoor temperature difference.

\[ E = \Delta T \times K \times S \times 24 \times d \times 3.6 \times 10^{-4} / COP \]  

where \( E \) is the calculated energy consumption for space heating (GJ), \( \Delta T \) the average temperature difference (°C), \( K \) the heat loss coefficient (W/m²K), \( S \) the floor areas (m²), \( d \) number of days for space heating, and \( \text{COP} \) the coefficient of performance of space heating equipment. The \( \text{COP} \) is different depending on the kinds of space heating equipment, and is assumed to be 0.82 for hot water heating panels, 1.00 for thermal storage heating equipment and portable kerosene heater, 2.79 for air conditioner in D04 and 3.08 for air conditioner in A01. The average temperature \( \Delta T \) can be calculated by equation (2).

\[ \Delta T = \frac{T_L S_L + T_B S_B - T_o}{S_L + S_B} \] 

where \( T_L \) is the temperature of the living room (°C), \( S_L \) the floor area of the living room (m²), \( T_B \) the temperature of the bedroom (°C), \( S_B \) the floor area except that of the living room (m²), and \( T_o \) the outdoor temperature (°C).

Fig.7. shows comparisons between calculated result and measured result. Most of the investigated values were less than the calculated values. One reason for this is that the calculation does not include the heat gain from solar radiation, equipment and the human body.

5. Conclusions

Energy consumption of two typical houses

(1) Energy consumption increased significantly in winter in both houses due mainly to space heating.
The energy consumption of kitchen, audio visual/information, healthcare, lighting and others are almost constant. The annual profile was similar between the two years.

(2) The correlation between energy consumption for space heating/cooling and the outdoor temperature is strong. On the other hand, correlation with the hot water supply is relatively weak. Energy consumption for the refrigerator becomes larger when the outdoor air temperature is higher, while energy consumption for the electric toilet seat is less when the temperature is higher.

**Energy consumption and temperature for 13 houses**

(1) Annual energy consumption per house varied from 40 to 120GJ/year. The difference of energy consumption between the two years was very small.

(2) In D01, where the energy consumption for space heating is the largest, the living room temperature is high and stable although the outdoor air temperature is remarkably varied. In D03, where the energy consumption for space heating is small, the living temperature is sensitive to outdoor air temperature conditions. In A01, where the energy consumption for space heating is between two extremes, the living room temperature varies considerably.

(3) Energy consumption for space heating was calculated, and most of the investigated values were less than the calculated values. One reason for this is that the calculation does not include heat gain from solar radiation, equipment and the human body.
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