Understanding Energy End-Use in New Zealand Houses

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ABSTRACT

The Building Research Association of New Zealand is conducting a long-term nationwide investigation into household energy consumption patterns. The objective is to build a model based on the main drivers that determine these energy consumption patterns. At present the temperatures and energy consumption of approximately 100 houses (out of a total of 400) have been monitored. In a subset of houses, the energy end-use consumption of most of the energy intensive appliances was measured. Data are being recorded with a time resolution of 15 minutes and higher for between six and twelve months. The inclusion of electricity, reticulated gas, LPG and solid fuel allows for the study of relationships between different fuel types. The temperature patterns within the houses are used as a measure of the energy service provided through the different means of heating. The households are also surveyed for their appliance ownerships and usage patterns, as well as for the socio/demographic characteristics of their occupants. This paper presents a brief overview of the project methodology and some of the data logging issues; then focuses on the data logging implications and analysis methods.

Introduction

The last major New Zealand investigation of energy use in houses was conducted by the New Zealand Electricity Department and the Department of Statistics (New Zealand Department of Statistics 1973). Since then –partly driven by the experience of the oil shocks in the late 70s– new technologies have found widespread acceptance, and the living patterns and socio-demographic composition of the population have drastically changed, but no reliable information was available.

The Household Energy End-use Project (HEEP) was established in late 1995 by a group of funding and research organizations as a long-term research activity to create a scientifically and technically rigorous, up-to-date public knowledge base of energy use and end-uses, energy services provision and key occupant, building and appliance determinants of energy use in residential buildings.

The reports published so far provide a detailed discussion of the project status and results (Stoecklein et al. 1997, Stoecklein et al. 1998, Stoecklein et al. 1999).

The objective of the HEEP work is to establish:

- how much energy is used;
- using which type of energy (electricity, gas etc.);

- by which domestic appliances (including heating and domestic hot water);
- at what time periods (season and time of day);
- when used by which type of household (socio-demographic);
- with which type(s) of occupant behaviour;
- in order to deliver what level of energy service i.e. room temperatures etc.

The activities so far have focussed on the development and implementation of a large-scale monitoring and data analysis methodology. Evidence from other studies (and supported by HEEP findings to date) shows that widening an energy end-use research study of this type from 10 houses to 100+ houses requires not only a quantitative increase in the amount of data to be collected and analysed, but also a qualitatively different approach (Sandusky et al. 1993). The HEEP study has in the meantime collected information from approximately 100 houses with another 29 houses currently being monitored in the Hamilton region.

Data Gathering and Monitoring

In a survey and building audit a range of data is collected on each house:

- Socio-demographic and physical surveys: in a face-to-face survey interview, information about socio/demographic characteristics of the household members as well as energy behaviour is collected. The survey lasts between one and two hours and is conducted by Building Research Association of New Zealand (BRANZ) staff.
- House plans: house plans are collected from the local council. These allow an evaluation of the thermal performance of the building, i.e. orientation of glazing, insulation etc.
- House audit: a walk-through house audit is conducted making note of building factors that affect energy consumption: insulation, thermal curtains, double glazing, hot water cylinder grade and settings, shower flow rates and general house conditions (dampness, mould, etc.). As part of the audit, information is also collected about major appliances, such as age, model, and power consumption. Photos are taken of all monitored appliances and the house exterior. The temperature and shower flow are measured.

In all houses the total and hot water electricity use is measured, as well as total energy use for each other fuel type (natural gas, LPG, coal, wood).

In a subset of houses the individual appliance energy consumption is also monitored.

- Electricity end-use monitoring: all major appliances, particularly heaters and hot water heating are monitored, but also refrigerators, TVs, washing machines, driers etc., as well as any fixed wired heating device(s), range, lighting, any detached buildings (e.g. garages), any other individually-wired fixed appliances and circuits. The metering equipment allows monitoring of up to eight power circuits. These eight channels are allocated in accordance to the ranking of the above list of monitored appliances.
- Reticulated gas: additional pulse-output gas meters are installed in the gas lines. These are connected to a small logging unit to measure gas consumption.
- LPG: thermocouples are installed in front of the LPG heater grill.
- Solid fuel: thermocouples are attached to the burner. The occupants are asked to record their approximate daily fire wood use for calibration purposes.
- Historical data: monthly electricity and gas usage records for the last five years are retrieved from the local utility company.

- Temperature monitoring: temperatures are logged every 10 minutes and provide information on how the house responds to changing external conditions and the use of heating and ventilation.
  - Internal temperatures: three to five sensors are distributed around each house.
  - External temperatures: one logger is placed outside most houses.

HEEP Data Collection Techniques

The average house monitoring cost in this project is approximately US$3000 per house, comparing to similar studies overseas, which are budgeting between US$4200 and US$8500 per monitored house (Bowman & Goldberg 1994).

This constraint required the development of low cost innovative monitoring approaches. In most cases, a trade-off had to be accepted between the accuracy of the results, labour intensity in data processing and the cost of the installation, data retrieval and equipment. Some of the methods have been tested only in the laboratory environment so far and we have not yet been able to verify the methods in the field. Some of the methods have been revised following the pilot study after discovering that the data quality was not acceptable.

Sampling Strategy

This project aims at developing quantitative relationships between socio-demographic occupant factors and energy consumption. As there is no guarantee that any significant relationships between the monitored data will be found, it is important to have a “fall back” option available. This includes the option of the collected data being used for average annual energy use estimations of the national household population. In order to use the data for this purpose it is desirable that the data are collected from a sufficiently large and representative number of houses to provide a statistically significant result.

The necessary sample size was determined from statistical analysis using data from a 1995 and 1996 pilot study of 28 Wanganui houses (Jowett 1997), by requiring less than 10% uncertainty in the mean at a 90% confidence level for

- annual total average household consumption
- day-time and night-time averages of hot water heating
- day-time and night-time averages of space heating.

The night-time average energy use for space heating is highly variable, which results in a required sample size greater than 1200. The reason for this variability seems to be the presence of night-store heaters. (Night-store heaters are electric resistance heaters with high thermal mass. Night-store heaters draw power during the night when power prices are low and release the thermally stored heat during the following day.) It is expected that the sub stratification of the sample in night-store heated and non-night-store heated households will reduce the required sample size. This hypothesis has not yet been tested due to the small sample size in the pilot study.

The sample size was set to 400 households, which is the required size for the total consumption and the hot water.

The second requirement concerning the “fall back” monitoring design is the representativeness of the collected data. It is met by selecting a random sample of households. The current approach is to use information from Statistics New Zealand, which is resolved on meshblock level, and to conduct random sub-sampling of households within the meshblocks. Meshblocks consist of blocks of between 20 and 100 houses within close proximity of each other.

The participation rate in the HEEP investigation is approximately 34%, i.e. approximately one third of the approached residents are willing to participate in the study. This compares to similar rates experienced in an Australian study (Mackintosh, Gangopadhyay and Tang 1994), however is much less than the 61% achieved in the US ELCAP study (Sandusky 1993). Reasons for refusals are sometimes technical ones such as house sale in the near future, changing occupancy, house modifications during the logging period etc. Often residents also refuse due to time constraints, reasons of principle or disinterest. One important difference between the US ELCAP study (Sandusky 1993) and the HEEP investigation is that the temperature loggers and some of the other loggers cannot be remotely offloaded, so that monthly visits into the house are required. Although, a disadvantage in this respect it also allows a convenient way to record household changes in terms of appliance ownerships or household composition. It also allows monthly rotation of the end use loggers between the different appliances.

The relatively high refusal rate biases the sample. A statistical analysis was conducted comparing socio/demographic factors of the HEEP sample households with the New Zealand average derived from the 1996 Census (Fitzgerald 1999). The encountered bias is sufficiently small to be corrected for by weighing the individual strata.

Half Year Monitoring and Annual Extrapolation

During the pilot study of 28 houses, we limited the monitoring period to approximately six months per house. This allowed us to double the sample size. Data were recorded over half a summer and half a winter period and the included transition season. The intention was to extrapolate the recorded time series to full average climate years.

The investigation of the monitored data shows that only a small number of appliance types show climate related energy use fluctuations. These include the heating energy use, lighting use and hot water energy use. Variation in energy end-use appears to depend on many factors, including time of year, temperature, sunshine, and occupant behaviour.

Annual extrapolation has been attempted for lighting, hot water and heating end-uses so far, based on external environment variables such as the day length and the external temperature.

Annual lighting extrapolation. Lighting circuits were monitored for 25 of the 28 houses from the pilot study. Plug-in lamps are not included and may be a significant but presently unknown fraction of the actual lighting used.

The graphs of the daily lighting demand show a trend for most houses of increased lighting demand during the winter months, as illustrated in Figure 1.

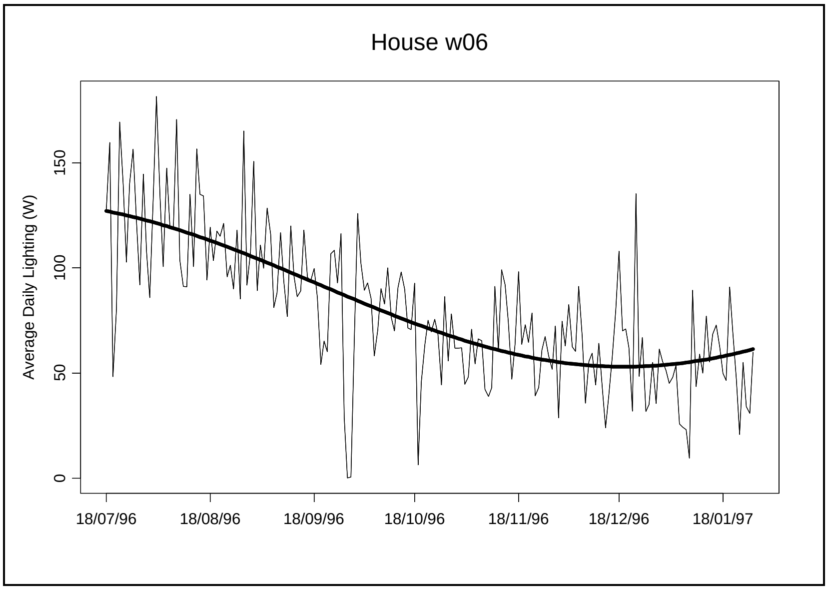

Figure 1: Lighting Energy Use Over Five Months

There is no obvious change observable in lighting energy demand for any house when daylight saving was applied (first Sunday in October) or removed (last Sunday in March). This may be due to an increase in evening lighting being offset by a decrease in morning lighting at daylight saving start and vice versa at daylight saving removal.

A cosine function with a one-year period centred on June 20th (the shortest day) is used to fit the average daily lighting demand. As shown in Table 1 this function gives reasonable representation of the seasonal trend for most of the houses. The standard error is calculated over the daily lighting energy use during the monitoring period. The application of this extrapolation method makes it is possible to predict the expected average lighting use for any day of the year.

House ID & Monitoring Period	r	Mean [W]	Std. Error [W]
w01: Apr96 – May96	0.75	227	41.4
w03: Apr96 - Jul96	0.13	122	37.1
w04: Apr96 - Jun96	0.55	104	38.8
w06: Jul96 - Jan97	0.93	92	25.2
w08: Jul96 - Jan97	0.93	32	18.2
w09: Jul96 - Jan97	0.88	11	7.57
w10: Jul96 - Jan97	0.88	88	32.6
w11: Mar97 - Jul97	0.78	91	40.1
w12: Mar97 - Jul97	0.44	55	19.1
w13: May97 - Jul97	0.32	43	9.24
w14: Mar97 - Jun97	0.87	3	0.79
w15: Apr97 - Jul97	0.61	51	35.4
w16: Mar97 - Jul97	0.78	8	12.6

House ID & Monitoring Period	r	Mean [W]	Std. Error [W]
w17: Mar97 - Jul97	0.77	91	31.3
w18: Mar97 - Jul97	0.63	33	21.4
w19: Jul97 - Jan 98	0.75	51	30.4
w20: Jul97 - Jan 98	0.80	52	19.6
w22: Jul97 - Jan 98	0.88	96	29.1
w23: Jul97 - Jan 98	0.84	36	15.5
w24: Jul97 - Jan 98	0.34	5	5.30
w25: Jul97 - Jan 98	0.97	7	3.78
w26: Jul97 - Jan 98	0.66	108	44.2
w27: Jul97 - Jan 98	0.95	23	6.62
w28: Jul97 - Jan 98	0.70	98	34.5
w29: Jul97 - Jan 98	0.89	25	8.05

Table 1: Correlation (r), mean annual wattage (W) and standard error of the measured data against the sinusoidal lighting fit.

As can be seen in Table 1 the monitoring period must be long enough to ensure successful parameterisation. The lights in house w01 were monitored for 1 month, which is inadequate to observe any seasonal variation. A period from the longest to the shortest day would be optimum, but 2 shorter periods, one in summer and one in winter, may be enough to parameterise the lighting. Houses w09 and w23 had broken periods of monitoring, but a reasonable graphical fit is still obtained.

Other annual extrapolation.

Hot water cylinders. Hot water cylinders heat water from the temperature of the main water supply to the pre-set thermostat temperature - as the temperature of the water supply drops more energy is required to heat water to the same temperature. HEEP monitoring to date has found a strong trend of higher hot water energy use during winter months compared to the summer months. The impacts of possible changes in water temperature and any occupant related factors have yet to be investigated.

The external daily mean air temperature is used to predict the daily average hot water energy use, using a linear regression model. The objective of this part of the analysis is the long term predictions and extrapolation of medium term measurements. Analysing average data improves the model fit eliminating some of the short-term occupant behaviour. The analysis is therefore performed using 13-day moving averages for the external temperatures and the hot water consumption. 13 days are approximately the time constant for air to ground temperature coupling to a depth at which supply water pipes are buried. The investigation shows that the correlation for the linear models is generally quite poor (average r^2: 39%). This may reflect the large impact of variant user behaviour. The average temperature dependency is 0.66kWh/day°C, with a median value of 0.27kWh/day°C.

Heating Energy. Heating energy consumption is largely dependent on occupant behaviour (New Zealand houses are generally heated by stand-alone heaters, which have no or only very simple thermostat controls and are generally not timer controlled.). Some households use ‘night store heaters’ but these are largely decoupled from the external temperature conditions, i.e. they are generally completely discharged at the end of the day, independent of the climate conditions. Other difficulties include the use of other that electric heating such as reticulated gas, LPG or solid fuel, which are difficult to measure.

One of the crucial requirements for a successful extrapolation is that the heating energy is monitored for a sufficiently long period and that it covers both the months of maximum usage and the months during which heating commences. This is often impractical using the half year monitoring schedule because of the technically unavoidable delays between removal of the equipment and the subsequent installation in the next set. Also, hysteresis effects cannot be easily identified on the basis of the short monitoring period.

For all these reasons it has proved difficult to establish correlation models of heating energy use, which would allow extrapolation the measured 6-month data to full years.

Annual extrapolation conclusion. Based on the above findings from the pilot study it was decided to abandon the half year monitoring schedule in favour of monitoring each set of houses for a full year.

Nevertheless, estimations of energy usage have to be made for ‘average’ climate years. This will require similar types of analysis as used for the annual extrapolation.

Monitoring of Different Fuel Types

Total Electricity Monitoring. The total electrical load is monitored with a time resolution of 2 minutes using commercially available Siemens S2AS electric meters with a pulsed output with a 1 impulse/Wh resolution. The signal of these meters is fed into a custom-built pulse logger.

The total load profiles are then disaggregated into their individual components.

T(t) is the time series of the sum of all appliances except for the hot water consumption, which is monitored separately. In addition to the total time series T(t), the typical power consumption of most of the large appliances (H for heater, F for fridge, etc.) is measured by connecting them individually to a power meter and switching them briefly on and off. For some appliances, this is quite inaccurate, since their power characteristics change with run time and appliance loading. It is, however, not feasible to use any more accurate techniques. The total time-series can be represented as $T(t) = H * H_d(t) + F * F_d(t) +$ etc. with $H_d(t)$, $F_d(t)$ etc. being dichotomous series indicating whether the individual appliance is 'on' or 'off'.

Because of the multitude of contributing appliances, solutions to the disaggregation can often be indeterminate, i.e. one appliance using 100W has the same effect as one with 30W and one with 70 W running at the same time, although it is generally unlikely that these two would turn 'on' and 'off' at the same time. A contributing difficulty is that some of the appliances have continuous load levels.

There are some indicators providing additional information on the total-load series composition. One indicator is time of day. It is unlikely -although not impossible- that cooking occurs at 3PM. Heating most commonly occurs in the evening when the occupants are at home. Another indicator is the runtime length, i.e. the length of the power plateau (i.e. fridges run approximately 0.25 hours, microwaves for 2-5 min etc.).

Most of these pattern characteristics can be picked up by visual inspection for each individual time series, each monitored house having different characteristics. They can then be used to automatically disaggregate the time series.

In order to develop these analysis tools appliance end use data were recorded with a two-minute time resolution in one of the monitored houses. The logging of the end uses allows an evaluation of the quality of the disaggregation method.

Two analysis approaches have been investigated so far:

1. Rule based separation of end uses
2. Pattern recognition algorithms using Artificial Neural Networks (ANN)

The first approach is based on specific rules, which are defined and applied to the total load profiles. These rules are similar to the ones used in other studies. However, one of the main assumptions in these studies is generally that the average daily shapes of individual 'end-use level' profiles are known. The disaggregation is then performed on the average daily profile of the total load, instead of disaggregating the non-averaged total load profile (Willink 1996, Bartels & Fiebig 1998, Akbari 1995, Bade 1987). Other rule based disaggregation techniques require the measurement of real and reactive power (Hart 1992). Our current measurement equipment does not record the reactive component, though.

Artificial neural network approaches to disaggregate time-series have been used, as well (Torkkola 1996, Yashimoto & Yakano 1998). Farinaccio et al. apply a combination of a rule based and a neural network approach (Farinaccio & Zmeureanu 1999). Farinaccio first applies filtering rules to each data point in the total load time series yielding a set of probability values for each appliance. These are then fed into a neural network, which makes the final classification whether the appliance is a contributor or not.

The following example from the HEEP investigation shows the extraction of the hot water consumption from the total load profile. Figure 2 contrasts the results from a rule-based algorithm with the ones from the neural network approach. It shows that during most of the time the predictions of both methods are identical.

The rule-based algorithm uses features such as the absolute value of the demand, the demand before and after the investigated time step and a number of smoothing functions. The ANN investigated is based on the Probabilistic Neural Network (PNN) paradigm. A set of the measured data is presented to the network together with the desired network output. In this instance, a modified time series of two-minute averages of the total load profiles over approximately half an hour is used as input values. The output value is a switch whether the hot water heating element is on or off.

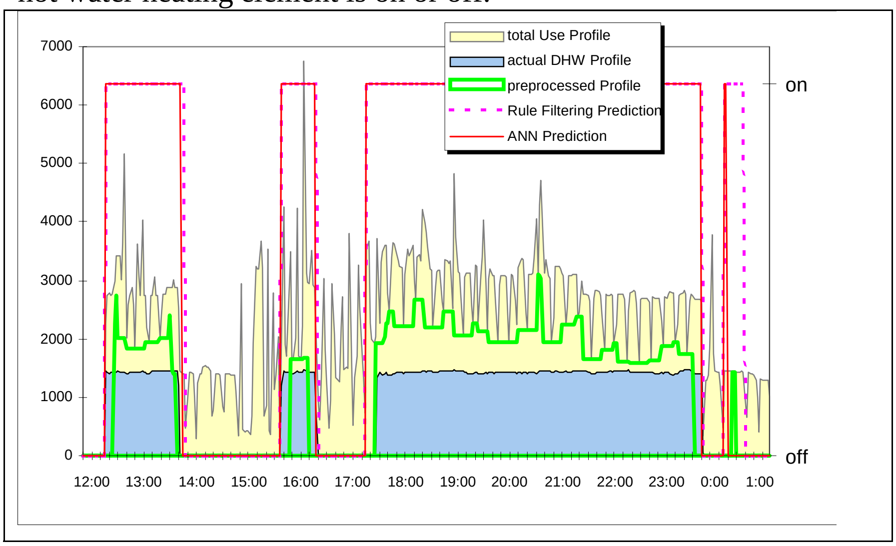

Figure 2:End-use disaggregation using a rule based algorithm and ANN

Initial results suggest that both methods have similar performance. A combined approach will be investigated which includes the initial definition of some indicators (Time of day, last switching amplitude, total current power, length of power plateau, etc) and then feeds these and the time series itself into a neural network classifier.

Reticulated Gas Monitoring. Reticulated gas usage is monitored using standard commercial gas meters with pulse outputs. These signals are fed into the same custom built pulse loggers as used for electricity. The conversion of the volumetric measurements into energy consumption and the accuracy of this method are described by Pollard (Pollard 1999).

LPG Monitoring. LPG heaters are un-vented bottled gas heaters using LPG, which is a combination of propane and butane. The current sample contains approximately 25% of houses with LPG heaters. Because one of the HEEP objectives is to understand the effects of fuel switching and potentially green house gas implications it is important to understand the energy use of these LPG heaters. Typical carbon emission factors for LPG are 60.4 t/TJ of CO_2 and 16.5 t/TJ tons of C (Baines 1993). Because these heaters release large amounts of water into the house during a season when occupants generally close doors and windows, these heaters are potentially also contributing to high moisture contents in the living spaces with the subsequent durability problems for the houses and health implications for the occupants.

During the first part of the pilot study, commercially available gas meters were used to record the LPG consumption. These meters are usually used for reticulated gas measurements. For LPG monitoring the meters were installed between the gas bottle and the heater. Because of their low energy resolution (280Wh per pulse) and other technical problems, this technique proved unsatisfactory.

A new method has therefore been developed. It requires the installation of three to four temperatures sensors (i.e. thermocouples) immediately in front of the LPG heater grill. Each of the LPG heaters is then calibrated by measuring the cylinder weight change against the temperatures of the sensors for the different heater settings. Most of the heaters have a number of discrete level settings, which often correspond to the number of sub panels of the heating element. The temperature measurements can then be used to determine the current heater setting. Using the calibration results, the settings can be correlated to a gas mass flow rate, which in turn can be converted into energy consumption.

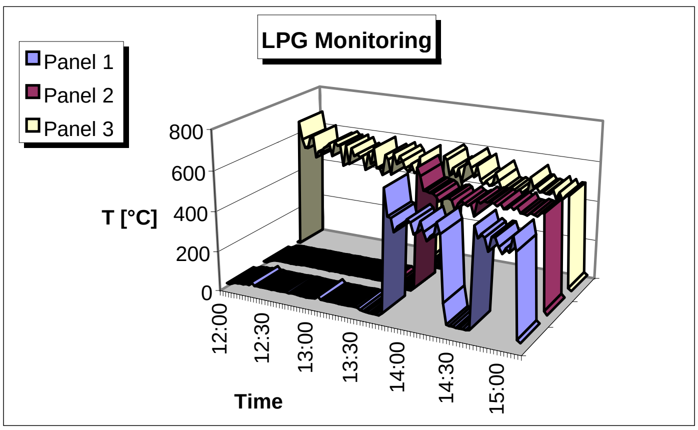

Figure 3: Sample LPG heater monitoring results.

Figure 3 shows some typical temperature readings in front of the three heating panels. The heater was run on the three different heat output settings – one element, two elements, and three elements - and the outputs from the thermocouples were recorded at two-minute intervals. The figure shows that the three different settings can be clearly distinguished.

The results of the heater calibration can be seen in the following table (Table 2).

Table 2: LPG calibration results

	Gas mass consumption [kg]	Burn time [h]	Consumption rate [kg/h]	Power [W]
Setting 1	0.124	1.27	0.098	1250
Setting 2	0.264	1.37	0.193	2470
Setting 3	0.640	2.30	0.278	3560

The mass of the cylinder was determined with an accuracy of 4 grams. The fluctuations in the measured temperatures seem to be more related to turbulences near the temperature sensors than to changes in the flow rate of the gas. The house occupants are asked record the date when they refill the gas bottles. This information will be used to cross check the temperature time series and the calibration.

The new method has proven to be very cost effective and sufficiently accurate. Reasons for inaccuracies include the fact that the mass flow rate of gas from an LPG cylinder changes as the volume of gas in the cylinder changes. Measurements of a small number of heaters indicate that the flow rate is reduced by approximately 4.5% between a full and a 20% filled cylinder. However, these changes cannot be detected in the temperature profiles because the composition of LPG gas (propane to butane) in the cylinder also changes due to the change in pressure in the cylinder. The net calorific values of propane and butane are different (46.3 and 45.7 MJ/kg respectively).

Solid Fuel Monitoring. Solid fuel consumption is currently monitored in a similar way as the LPG consumption, using high temperature thermocouple loggers to record the temperatures in close proximity to the fire. The calibration in this case is done on the basis of log-book entries by the occupants covering daily amount of burnt fire wood, approximate burn time and wood type. Initial analysis of the data using a method described by Modera (Modera 1985) show satisfactory results, although no quality check can be performed because of the complexity and cost that would be involved in monitoring actual reference heat outputs of heaters.

Temperature Monitoring. Temperatures are being monitored in three different locations within each house. In order to be able to analyse vertical stratification and zoning effects two temperatures are being monitored within the heated living zone and one temperature in the – usually unconditioned- master bedroom. One of the living room loggers is placed at approximately 2m height, the other at approximately 0.4m height.

During the pilot study and in a subsequent joint research program some of the houses were equipped with up to ten temperature loggers. Principal component analysis of this data has shown that the two temperatures in the living area and the third temperature in the bedroom can explain more than 80% of the temperature distribution within the house (Pollard & Stoecklein 1998).

External temperatures are being monitored in close proximity of most monitored houses. Other information, such as sunshine and precipitation is taken from the climate database of the National Institute of Water and Atmospheric Research (Penney 1997).

Surveys Instead of Occupancy Sensors. Experience showed that on several occasions it would have improved the data analysis if the occupancy of the building had been monitored. Typical examples include the analysis threshold temperatures when people start heating or the understanding of ventilation behaviour, since the window opening behaviour of the occupants generally depends on them being at home.

The monitoring of room occupancy is felt as a significant intrusion into the privacy of the house residents. In order not to reduce the participation rate in the project any further, these measurements were dispensed with. The occupancy is instead inferred from other energy recordings, such as light, cooking, TV and washing machine usage.

Conclusion

The Household Energy End Use Project (HEEP) is a long-term research program with the objective of determining and modelling energy use in New Zealand residential buildings. A range of physical determinants of energy use, including the building and the appliances within it, as well as the socio-demographic aspects of the occupants, are included in the analysis and in the model.

A large number of different monitoring and analysis techniques were applied. Some of the investigated methods have been adjusted after the experiences from the pilot study. The current set of measurement techniques promises to be sufficiently accurate and has lead to some interesting initial results.

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