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The Household Energy End-Use Project: Measurement Approach and Sample Application of the New Zealand Household Energy Model

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THE HOUSEHOLD ENERGY END-USE PROJECT: MEASUREMENT APPROACH AND SAMPLE APPLICATION OF THE NEW ZEALAND HOUSEHOLD ENERGY MODEL

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ABSTRACT

The Household Energy End-Use Project (HEEP) is a long-term study with the objective to measure and model the way energy is used in New Zealand households. The envisaged model will use physical building and appliance characteristics as well as socio-demographic factors to describe the energy consumption patterns and some of the energy services, in particular the achieved indoor temperatures. The model will be used to understand current and future national household energy requirements, and as a tool to evaluate the implications of building and appliance performance changes.

The project commenced in 1995 with a pilot study. At present approximately 100 households have been monitored for 5-11 months each recording energy consumption profiles, temperature patterns, physical properties of building and appliances and socio-demographic factors.

This paper describes three aspects of the monitoring methodology and the preliminary data analysis.

The paper discusses the development of a cost-effective methodology for monitoring and interpreting temperature patterns within a house covering vertical temperature stratification and temperature zoning effects. Some of the initial results on temperature patterns found in New Zealand houses are temperature stratifications of up to 4°C and comparatively low average room temperatures, indicating that New Zealand houses are often under-heated.

The second part of the paper describes a methodology to extract the main thermal building parameters (building conductance, thermal mass and solar aperture) from the measured energy and temperature time series. The method is based on a previously developed Short Term Energy Monitoring (STEM) technique. The analysis results are used to calibrate a simple heating energy calculation model (ALF), which is used for New Zealand building code compliance verification.

The third part discusses various aspects of electricity demand profiles. It briefly describes a profile classification methodology using artificial neural networks. It then outlines an example of how this information will be linked to socio-demographic household factors and the way in which energy supply cost scenarios can be implemented in the model. The example highlighted in this paper shows that occupants on superannuation have clearly different energy usage patterns associated with above average unit supply costs.

Even at this preliminary stage of data monitoring and analysis, HEEP provides some interesting findings, highlighting areas of current information gaps and required performance improvements in New Zealand houses.

KEYWORDS

Energy monitoring; Household energy model; Indoor temperatures; Socio-demographic factors; Thermal building performance

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 (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 organisations 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. Several reports and papers published so far provide detailed discussions of the project status and results (Stoecklein et al., 1997, Bishop et al., 1998, Camilleri et al., 1999, Stoecklein et al., 2000).

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. The HEEP study has in the meantime collected information from approximately 126 houses, including 29 houses monitored in the Hamilton region during the 2000 year.

This paper presents preliminary results on temperature patterns, building thermal performance measurement methodology and the development of electricity time-of-use profiles.

TEMPERATURE PATTERNS IN NEW ZEALAND HOUSES

Space heating is an important end-use in New Zealand's houses (Stoecklein et al., 1997). The energy used by space heating in a house is determined by the climate, the physical properties of the building, and the comfort expectations of the occupants. Predicting future energy demand for space heating is complicated by the increasing comfort requirements of the occupants (Wright and Baines, 1986). When the insulation levels of houses are increased the expected technical savings are not achieved, as the occupants tend to use a fraction of the savings to increase the temperature within the house. As the temperature levels in New Zealand houses appear to be low compared to other countries (Isaacs, 1998, Stoecklein et al., 1998, Pollard et al., 1998a&b), these increases in temperature may have other benefits than energy savings, such as improvements to health (National Health Committee, 1998).

In order to better understand future spacing heating demand changes, the HEEP work has included a detailed examination of air temperature distribution patterns in a selected number of houses. This work has investigated issues of time scale (how often to measure temperatures) and temperature distribution (how does temperature vary spatially)

The time scale is the lesser of the two issues. The air temperature needs to be measured at a rate long enough to be consistent with the time constant of the sensor, but also with a high enough frequency to detect trends in heater use, as well as the variation in the external climate and time of day, while not being confused by small fluctuations. After experimentation a period of 10 minutes has been used in the majority of HEEP houses, although finer resolution is used for specific investigations.

The temperature will vary within the house, both by which zone or room the logger is located, and where within that zone or room the logger is placed.

One subset of the HEEP data includes nine houses where up to four temperature measurements of differing heights were made in the living room as well as measurements from other rooms within the house. Each of these houses had between eight and ten locations monitored. These houses are not heated uniformly – an initial principal component analysis of the dataset has revealed a distinction between the main bedroom and the living area as most significant (Pollard, 2000).

A dominant feature of air temperature variation within a room, is the systematic variation with height (vertical temperature stratification). In order to establish a vertical temperature profile, temperatures at a number of measurements points at various heights need to be gathered. Information on the vertical stratification of air temperature was examined (Pollard, 2000) by using data from temperature data-loggers placed at heights of 0.4m, 0.9m, 1.4m and 1.9m in a corner of a living room within a Palmerston North house. Approximately 25 days of 5-minute data (288 measurements per day) was collected from each of the data-loggers. Four days of measurements are shown in Figure 1, with time on the x-axis (midday is indicated by the vertical lines through the date labels) and height on the y-axis. The shading, to the scale on the right, indicates the temperature in 1°C increments.

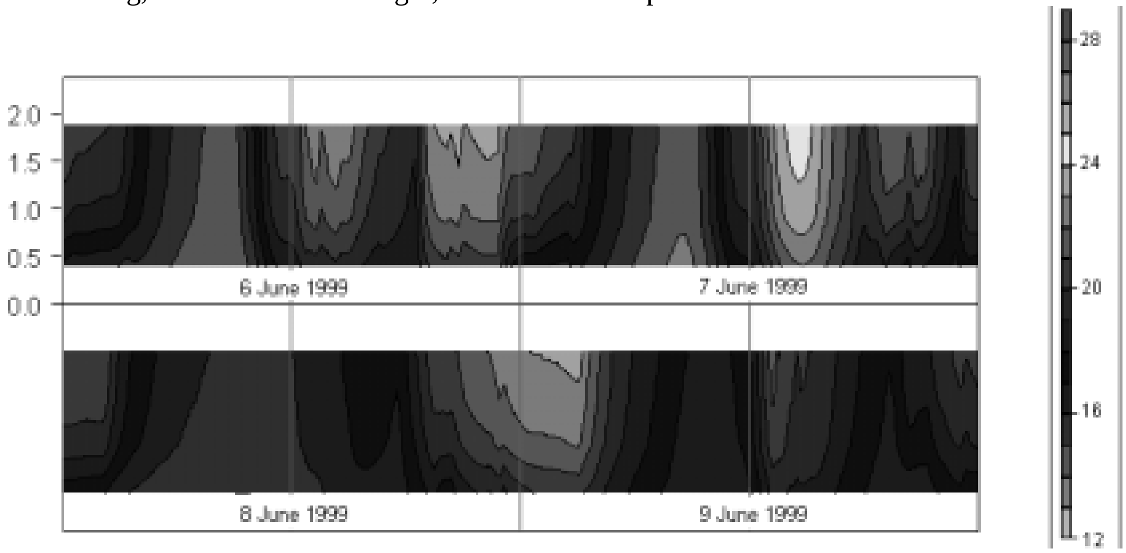

Figure 1: Vertical temperature profile in a living room in a house in Palmerston North

The increase in room temperatures in the afternoon is due to solar gains through the north-facing glazing, while the evening increase is due to the use of a flued gas heater. The shape of the temperature increase is 'stalactite' in shape – with up to a 4°C difference over the 1.5 m height difference at maximum temperature.

The results confirm that within a room, care must be taken with the placement of the temperature loggers to ensure the measured temperature is representative of the air temperature of interest. The loggers should be sufficiently far away from the wall, ceiling and floor, or any heat source or sinks (heaters, windows, etc.) where draughts may be present. The logger should not be in direct view of any radiation sources such as direct sunlight, household lighting and radiant heaters, or located near any direct heat source (Lyberg, 1993).

The temperature stratification illustrated in Figure 1 is directly related to the presence of a direct source of heat – whether solar radiation or a heating appliance. Analysis of the nine house subset is being used to relate the measured temperatures to likely room temperatures under a range of different 'heat' regimes.

Measured temperatures

New Zealand houses have traditionally been only heated to low levels. Although there was no measured evidence to support it, it was assumed that New Zealanders have started demanding more comfortable temperatures and that average temperatures have risen.

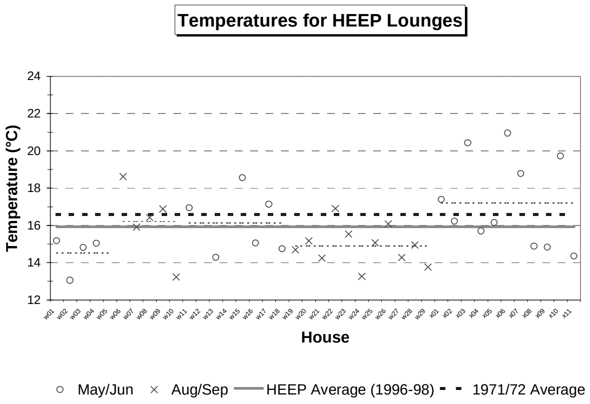

Figure 2: Average living room temperatures

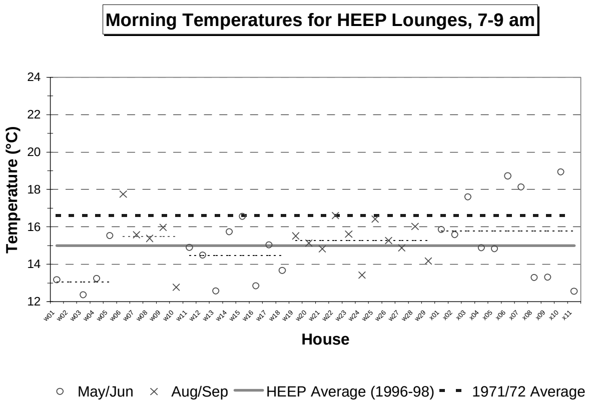

Figure 3: Morning temperatures

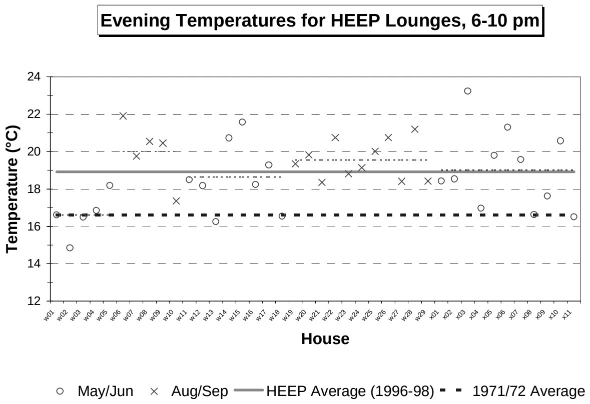

Figure 4: Evening temperatures

The 1971/72 study measured average winter temperatures in August-September 1971 in three locations – kitchen, lounge and main bedroom (Department of Statistics 1976). The following three figures provide an comparison of temperatures found in 40 HEEP houses in the lower part of the North Island (individual points and solid line) with the 1971 average (dotted line). As the early HEEP monitoring was for six-month periods, the point symbols indicate the measurement periods – May-June or August-September

Figure 2 compares the average living room temperatures (i.e. the temperature averaged over all days and all hours). The HEEP (15.9°C) and 1971 averages (16.6°C) are very close, suggesting little, if any, significant shift in average temperature over the 25 years.

Figure 3 limits the HEEP data to only the morning hours (6 am to 9 am) (average 15.0°C) while the 1971/72 data remains an overall average. The HEEP average morning temperature is 0.9°C lower than the overall HEEP average.

Figure 4 limits the HEEP data to the evening hours (6 pm to 10 pm) (18.9°C), while the 1971/72 data is unchanged. The HEEP average evening temperature is 3°C higher than the overall HEEP average.

The patterns could suggest that while heaters are used in the early morning, there is insufficient time to achieve comfort temperatures. In the evening the longer operating time permits higher comfort temperatures to be reached. An alternative view could suggest that living areas are only used in the evenings, and in the morning this space is unheated. HEEP will be undertaking detailed analysis of heating energy use and temperature patterns, and expects to provide valuable information to assist in better meeting house occupant comfort expectations.

EVALUATING THERMAL BUILDING PERFORMANCE PARAMETERS

A short-term energy testing (STEM) method was developed to enable quicker monitoring and prediction of annual space heating energy use in typical New Zealand houses. The method follows in general the approach developed by Sonderegger (Sonderegger et al., 1980), and is based around two simple tests:

- **Co-heating**, to determine the total heat loss coefficient in W/°C (UA-value). In this test, the house is heated with electric resistance heaters and the space temperature is held constant over a 24-hour period.
- **Cool down**, to determine the effective thermal mass in Wh/°C. In this test, the house is heated to a constant temperature and then is allowed to cool overnight with minimal heating energy input.

These two thermal parameters, together with an estimate of the solar gains from a building audit, describe the house in enough detail for an energy calculation procedure to predict the annual heating energy use. This analysis was intended to establish whether the STEM method could be used in conjunction with the BRANZ ALF3 thermal building calculation tool (Stoecklein et al., 1999) to model the heating energy performance of the monitored houses and ultimately of the housing stock.

Table 1: STEM parameters for the controlled heating experiments.

House ID	**Heat Loss Coefficient (W/°C)**			**Effective Thermal Mass (Wh/°C)**	
	Calculated from plans	Measured during STEM testing	Difference %	Calculated from plans	Measured during STEM testing
1	113	124	+10 %	466	1,400
2	643	515	-20 %	1,245	4,150
3	796	587	- 26 %	2,556	6,270
4	568	505	-11 %	2,068	6,500

Table 1 shows that the measured heat loss coefficients were generally similar to those expected based on an analysis of the house dimensions and construction. The differences could usually be explained in terms of assumed values for insulation levels that were not well known.

The most important practical lesson learned was that ambient temperatures above about 10°C yield inconsistent results, especially for cool down tests to determine thermal mass. This 10°C ‘rule of thumb’ may be applicable only to houses with heat loss characteristics in this range. For example, much better insulated houses could require even colder nights to achieve good cool-downs.

Only data from the period between midnight and 6 am was found to be useful for data analysis. The thermal zoning and the placement of heaters affected the calculated heat loss coefficient for a house therein. Although this may seem apparent in retrospect, this point was not noted anywhere in the literature search (Balcomb et al., 1993, Fels, 1986, Liu et al., 1995, Saunders et al., 1994, Subbarao, 1988, Subbarao et al., 1990). Overseas researchers have apparently neglected this point, and assumed that internal temperatures were consistent throughout the entire space of their houses, which as discussed earlier is not the case in New Zealand homes. This effect is exacerbated by the relatively small indoor-to-outdoor temperature differences experienced in most New Zealand houses.

The method has been demonstrated to work with acceptable precision, and to allow the quick measurement of thermal parameters of typical New Zealand houses (Bishop, 1998).

Extracting the thermal performance parameters from normally occupied HEEP houses

For a subset of occupied HEEP houses the 10-15 minute time resolution data were grouped according to temperature. Temperatures were calculated as a simple average of all internal temperature sensors.

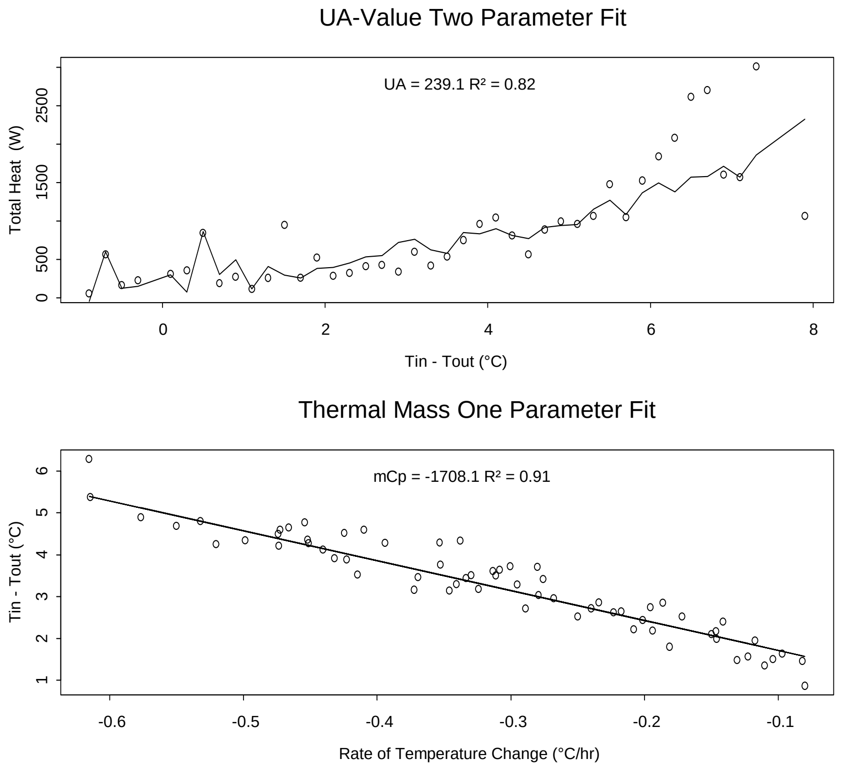

Figure 5: Fitting of UA-value and thermal mass

The whole house heat loss coefficient (UA-value) was estimated using selected periods of data during fixed evening hours after sunset. Total heat included applied heating, electrical and gas load and occupant load. Data were selected from periods when the rate of change of temperature was low, to minimise the effects of thermal mass, and to avoid warm-up loads. Parameters were estimated from a two-parameter robust regression (top plot in Figure 5).

The whole house thermal mass was estimated using selected periods of data during the early morning, from around midnight to 6am. Data were selected only for periods when the temperature was not increasing, and the applied heating energy was low. This was to minimise the effects of applied heating, avoid recharge of the thermal mass, and minimise the difference between the thermal mass temperature and the internal temperature. The thermal mass was estimated from a one-parameter robust regression (bottom plot in Figure 5).

The fits resulted in the parameters shown in Table 2. The matches of the UA-values with the building audit results have in general a similar quality as the ones in the controlled heating experiment. The methodology requires quite a number of estimates, which may lead to a larger uncertainty of the results than in the controlled measurement technique. However, this uncertainty seems to be counterbalanced by the larger amount of available data. The thermal mass data are difficult to compare with the ALF3 thermal mass coefficients, because of a fundamentally different interpretation. The quality of the match can still be estimated by investigating the proportionality of the deduced and the ALF3 values. Table 2 shows that the proportionality coefficient is relatively constant, indicating a reasonable match.

*Table 2: Comparison of STEM and ALF UA-value and thermal mass estimates. (* X04 had a solid fuel heater).*

HEEP #	**Heat Loss Coefficient (W/°C)** Deduced from monitoring	Calculated from plans	Difference %	**Effective Thermal Mass (Wh/°C)** Deduced from monitoring	ALF3 thermal mass coeff.	Deduced/ ALF3
X02	625	504	-19 %	9584	313	30.6
X04	376	629	* +67 %	3046	398	7.7
X07	594	482	-19 %	8144	462	17.6
X08	239	303	+27 %	1708	146	11.7
X09	1305	1119	-14 %	10864	592	18.4
X10	205	249	+21 %	2912	201	14.5
X11	774	633	-18 %	5856	295	19.8

CLASSIFICATION OF ELECTRICITY TIME-OF-USE PROFILES

The pattern of energy use in a house during the day will be driven by a wide range of internal factors, including the number of people in the house, the pattern of work, the age of the occupants, etc. As well as time-of-day energy and temperature monitoring, the HEEP study collects extensive information on the socio-demographic characteristics of the household occupants, as well as data on appliances and house thermal envelope. If a specific set of factors can be linked to a specific class of consumers, this may create the opportunity to advantageously manage part of the demand pattern, to forecast the impact of changes in the demographic composition of the customer base or to identify new consumer groups with beneficial load pattern characteristics (Stoecklein et al., 1998).

Time-of-day energy use data from 40 HEEP houses was analysed to determine generic daily demand profiles, and these then used to extract user profile classes. These profile classes were then correlated with the household physical and/or socio-demographic characteristics.

The energy load profiles of most houses vary considerably during the year, principally due to external climatic factors. Space heating, which accounts for some 30-40% of household energy consumption, is used primarily over the winter season and almost not at all in summer. Because of this, the analysis was conducted on monthly average-day profiles. This provides one day-profile for each house for every month the house is monitored – in this analysis, 239 profiles were used. Although this is a large number of individual profiles, the analysis cannot be regarded as being fully representative, as each household profile can be expected to correlate between months.

Two approaches can be chosen in respect to the profile classification:

Profile shape: analyse the profile shape while disregarding the quantitative level of the consumption i.e. the profiles are defined as percentages of the maximum average usage for each particular house and month. The advantage of this approach is that timing and period of the peaks determine the category, more than the absolute size of the peak. When this approach is taken, then attempts to shift the peaks to other periods of the day will result in an actual peak shift, however with varying contributions according to the absolute peak height of the particular household.

Absolute power demand: The second approach takes account of the absolute power demand in the daily profiles. This type of classification leads to the grouping of high power consumers versus low power consumers. The actual use profile of the grouped households becomes less significant.

The 239 monthly average-day profiles were classified using a Kohonen probabilistic neural network (Kohonen, 1984). This type of network classifies patterns without ‘supervision’, i.e. it defines its own criteria, yet still allows the user to set the number of categories and some of the learning parameters.

The six profile classes determined by the network are shown in Figure 6, with each line representing the daily electricity profile for one house averaged over one month. . The x-axis represents a 24-hour day period. The thick black line shows the average profile of the class. The inserted pie charts show the proportion of superannuatants (S) and non-superannuatants (nS) included in each class.

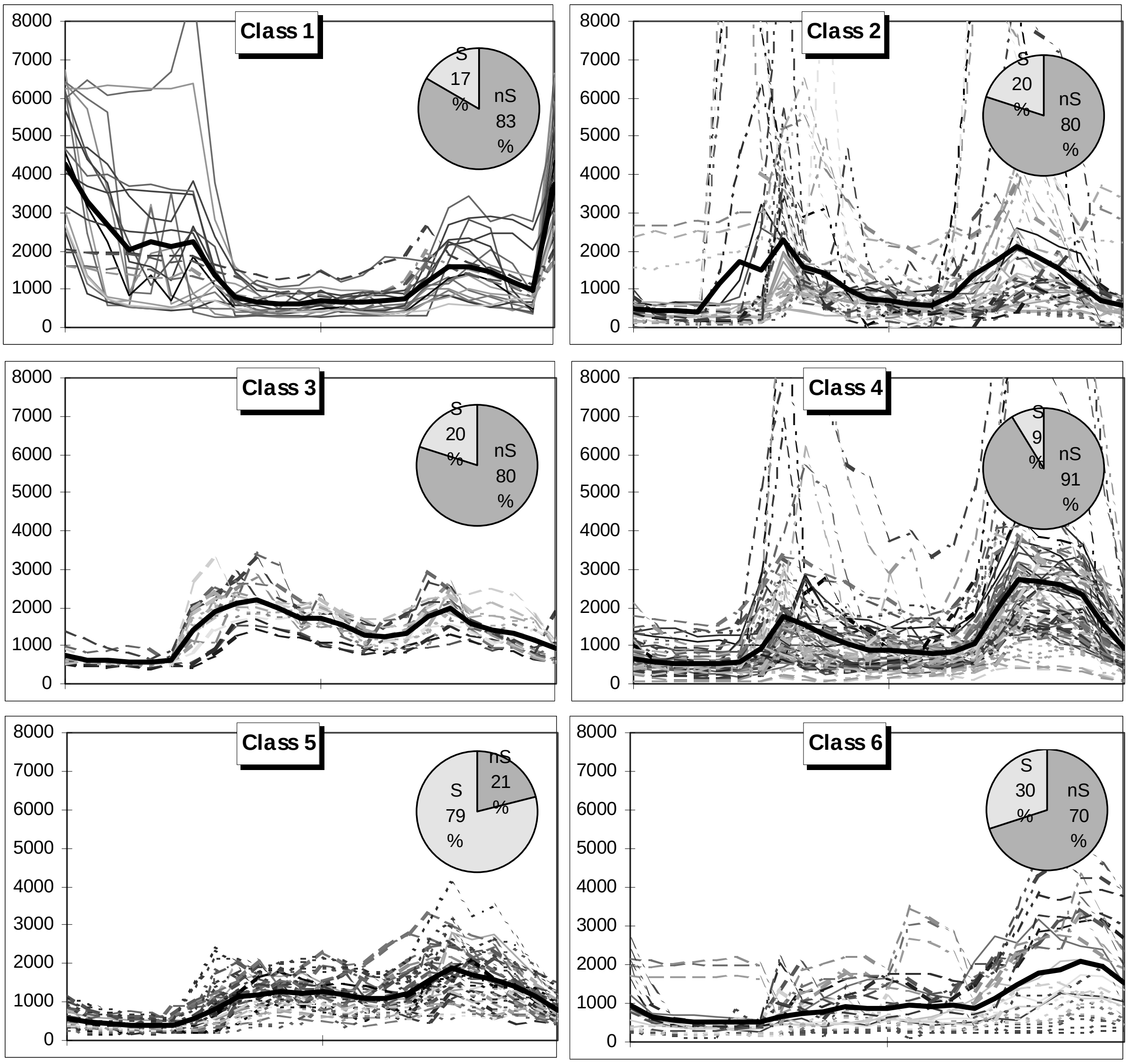

Figure 6: Daily electricity profiles in watts (x-axis: midnight-to-midnight)

The following classes can be distinguished from Figure 6:

- Class 1: Typical night-rate profile: high night use, flat low day use and medium evening peak.
- Class 2: Morning and evening peaks about the same height. Morning peak comparatively short.
- Class 3: Flat profile with high morning peak.
- Class 4: Distinct sharp mid morning peak, low midday and high extended evening peak.
- Class 5: No clear morning peak, medium afternoon level and early evening peak.
- Class 6: Similar to Class 4, but later evening peak and lower overall level.

A more detailed investigation of the contributing profiles indicated that houses tend to either have a non-changing profile class for the whole year, or they belong to two classes with the change generally occurring between September and October, and between March and April. This is a strong indication of the occurrence of an abrupt profile change caused by the use of room heating devices.

The chart in Figure 6 also shows an example of the way in which socio-demographic data can be linked to a profile class. The inserted small pie charts show the breakdown of each profile class, over the winter months, based on whether the occupants' main income is superannuation. Class 5 stands out with nearly 80% of its component profiles from superannuatant households (S), while all other classes consist of mainly non-superannuatant households (nS).

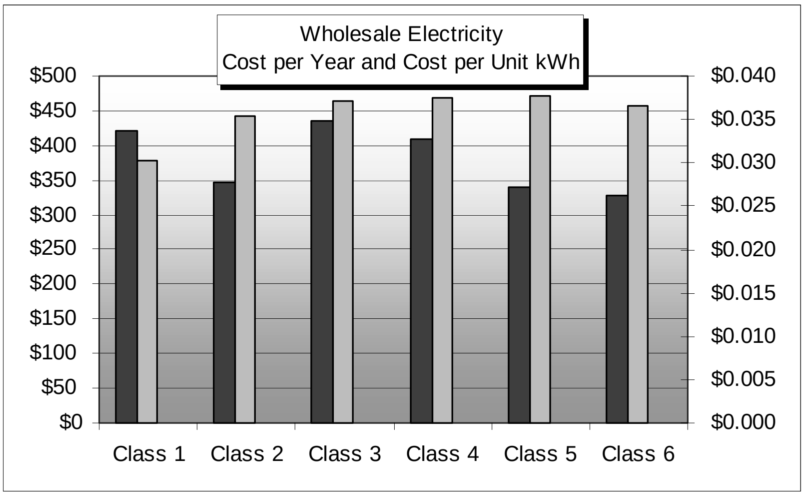

Figure 7: Wholesale electricity cost by profile class (annual cost in left columns with left y-axis, cost per kWh in right columns with right y-axis).

Using half-hourly wholesale electricity prices and linking these with the energy use profiles for each profile class, it is possible to determine the energy cost of supplying electricity to a particular class. The graph in Figure 7 shows the average annual wholesale electricity cost for the six different profile classes. The data indicate the annual electricity supply cost for superannuatants (Class 5) is smaller than for most of the other classes. However, a closer inspection also shows that the per kWh supply cost for the Class 5 is the highest one of all the classes, i.e. superannuatants prefer to use electricity during the high cost periods. This would indicate that demand avoidance and shifting programmes might be most effectively targeted at this customer group.

The profiles in this analysis are total load profiles, which are of particular interest for electricity providers. However, these profiles consist of contributions of all the separate appliance profiles. It is conceivable that occupants in two households could follow the same appliance profile class for one appliance but different ones for another appliance. This would effectively 'wash out' the class of total load profiles. To use the profile for demand shifting, it is necessary to know the contribution of each appliance, and thus a similar analysis will be conducted for each appliance type. Once this is completed, a correspondence analysis can be conducted to establish links with physical and socio-demographic variables.

It could then be determined which of the household appliances contribute most to the supply cost. This then allows targeting any load shift and load reduction measures in a very controlled way to a specific user class (super annuitants) and a specific appliance group (for example heaters).

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.

The indoor temperature monitoring methodology has been investigated in detail, with particular focus on thermal zoning within the houses and thermal stratification effects. Stratification differences in excess of 4°C were found. Averaged monitored temperatures in 37 HEEP houses were compared with historic ones from 1971/72. No significant change in indoor temperatures could be detected.

Two methods were investigated to extract the main thermal building performance parameters from measured data. Both, the controlled short-term measurement approach (STEM) and the analysis of long-term occupied house data show promising results.

Neural network classification algorithms were used to determine electricity user profile classes. The correspondence of different profiles and other socio-demographic household information has considerable potential for commercial analysis and demand management in the electricity marketplace. It provides important information on the cause and links of certain profiles, and thus allows targeting of specific electricity consumer groups.

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