STUDY REPORT

SR 221 (2010)

Energy Use in New Zealand Households

Final Report on the
Household Energy End-use Project (HEEP)

Nigel Isaacs (Editor), Michael Camilleri, Lisa Burrough &
Andrew Pollard (BRANZ Ltd),
Kay Saville-Smith & Ruth Fraser (CRESA),
Pieter Rossouw (CRL Ltd),
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- Cement and Concrete Association of New Zealand
- PowerCo, Wanganui
- TransAlta New Zealand Ltd, Wellington
- TransPower New Zealand Ltd
- WEL Energy Trust, Hamilton.

The HEEP team is also grateful to all the house occupiers who have responded to our questions and permitted us to monitor their homes. Without their cooperation this research would not have been possible.

Note

This report is intended for anyone interested in how, why, where and when energy is used in New Zealand households. It will be of interest to researchers, policymakers, product suppliers and manufacturers, designers.

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Reference

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Abstract

This is the final report on the Household Energy End-Use Project. It brings together and updates material presented in previous reports, as well as providing new analysis.

HEEP was a multi-year, multi-discipline, New Zealand study that monitored all fuel types (electricity, natural gas, LPG, solid fuel, oil and solar used for water heating) and the services they provide (space temperature, hot water, cooking, lights, appliances etc) in a national, random sample of about 400 houses. Data collection was completed in 2005.

The report provides baseline information on the hows, whys, wheres and whens of energy use and the services provided. The report includes sections dealing with: the development of the Household Energy End-use Resource Assessment Model; winter and summer temperatures; a case study of Hamilton pensioner houses; forest casting aggregate energy use based on household socio-economic variables; fuel poverty; hot water energy use; wood and solid fuel heating; LPG heater use; effect of mandatory insulation on energy use; heat loss and thermal mass; appliance ownership; standby and baseload electricity use; faulty refrigeration appliances; load factors; domestic hot water; ALF modelled energy use compared to actual energy use. Sections also provide detailed background to the research design and methodology, and publications resulting from the research.

KEYWORDS

Energy, temperatures, space heating, domestic hot water, appliances, fuel poverty, energy policy, fuel use, electricity, natural gas, wood, LPG, residential energy, energy end-uses, energy consumption.

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1. INTRODUCTION

The discovery of new sources of energy, generation processes and transmission are considered to be critical to society. But what uses all that energy? HEEP (the Household Energy End-use Project) provides answers for the New Zealand residential sector.

HEEP was a multi-year, multi-discipline research project that has involved detailed energy and temperature monitoring, occupant surveys and energy audits of some 400 randomly selected New Zealand houses. HEEP is unique in that no constraints were placed on fuel use – whatever fuel was used in the house, it was monitored, including electricity, natural gas, LPG, coal, wood, oil and solar water heating. Monitoring used electronic dataloggers recording at intervals of 10 minutes or less (Camilleri, Isaacs and French 2006). Data collection was completed in 2005.

This is the final HEEP report, providing coverage of the entire project and full results. Additional information, including downloads of paper reprints, is available from the BRANZ website, www.branz.co.nz.

1.1 HEEP monitoring overview

Figure 1 shows a map of the monitoring locations, while Table 1 summarises details of the randomly selected HEEP houses. Locations circled in Figure 1 are the stratified sample selections in the urban areas, while the other locations are cluster sample selections.

HEEP used a population weighted sampling framework based on major urban areas ('strata') and the rest of the country ('clusters'). The strata included 221 households from Auckland, Manukau, North Shore, Waitakere, Tauranga, Hamilton, Wellington, Upper Hutt, Lower Hutt, Porirua, Christchurch, Dunedin and Invercargill. The remaining 178 households were selected from 19 area unit clusters of eight, nine or 10 houses drawn at random, with a probability proportional to the number of households from those not covered by the major population regions – from the far north to the deep south.

For the purposes of analysis some of the strata for the metropolitan areas have been combined into Auckland, Hamilton/Tauranga and Dunedin/Invercargill. The clusters (rest of New Zealand) have been split into 'warm' and 'cool', with the warm clusters being those areas where the annual heating Degree Days according to ALF are less than or equal to 620.

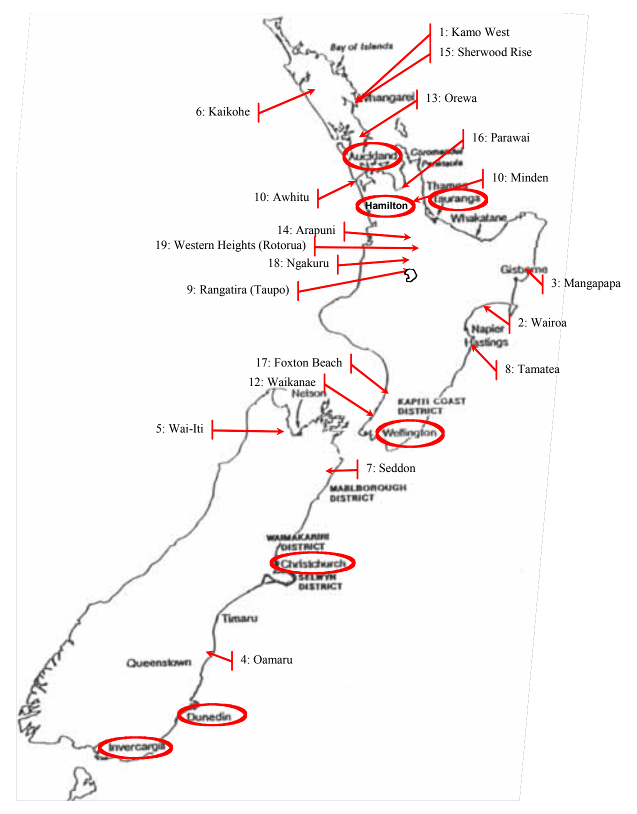

Figure 1: Map of New Zealand showing HEEP monitoring locations

Regional Council	Location	No. of houses	Year(s) monitored
Northland	Kaikohe	10	2003-04
	Kamo West	10	2003-04
	Sherwood Rise	10	2003-04
Auckland	Orewa	8	2004-05
	North Shore	19	2001 & 2002
	Auckland	37	2001 & 2002
	Waitakere	16	2001 & 2002
	Manukau	24	2001 & 2002
	Awhitu	9	2004-05
Waikato	Parawai	9	2004-05
	Hamilton	17	2000
	Arapuni	10	2003-04
	Ngakuru	9	2004-05
	Rangatira	9	2004-05
Bay of Plenty	Minden	10	2003-04
	Tauranga	9	2003-04
	Western Heights	9	2004-05
Gisborne / Hawkes Bay	Mangapapa	9	2004-05
	Wairoa	9	2004-05
	Tamatea North	9	2004-05
Wanganui	Foxton Beach	10	2003-04
Wellington	Waikanae	10	2002-03
	Wellington	41	1999
Tasman	Wai-iti	9	2004-05
Marlborough	Seddon	9	2004-05
Canterbury	Christchurch	36	2002-03
Otago / Southland	Oamaru	10	2003-04
	Dunedin	14	2003-04
	Invercargill	6	2003-04
All NZ	**Total**	**397**	**1999-2005**

Table 1: Location, count and year monitored for HEEP houses

HEEP monitoring was based on 10 minute records. The majority (74%) of houses simply had the total use of each fuel type as well as the domestic hot water (DHW) heater monitored. In the remaining houses, detailed monitoring of all significant fuel use was undertaken. Two types of electric end-use monitoring systems were used:

- EUM – a purpose-built, commercial, power line carrier system that monitored up to eight fixed electric circuits (e.g. lighting, stove etc) and up to eight remote uses (e.g. dishwasher, television etc)
- Siemens Appliance Monitoring (SAM) – a standard Siemens revenue meter with a pulse output that fed into a BRANZ Ltd datalogger.

HEEP also made early use of the remote reading electric 'smart metering' developed by Energy Intellect Ltd (formerly Total Metering Ltd). Since 2002, three sets of meters were placed on three houses for one year. They replaced other HEEP electricity metering, and provided both real and reactive power every minute.

Apart from the early houses in Wellington, at least one bedroom and two living room temperatures were recorded.

In addition to the ongoing monitoring, a detailed occupant survey, hot water audit and energy audit were conducted during the installation.

The data is held in a database for analysis by the appropriate statistical tool, which includes S-Plus and GenStat. Where appropriate, details of the statistical tests and results are provided in this report. Further information on these is available in any standard statistical handbook.

1.2 HEEP in action

Over its life, HEEP has contributed to a range of policy and informational changes. This section provides a brief summary of the known direct consequences, though it is expected that there were others and that the results will continue to contribute to the development of energy policy, planning, efficiency, and house and appliance design.

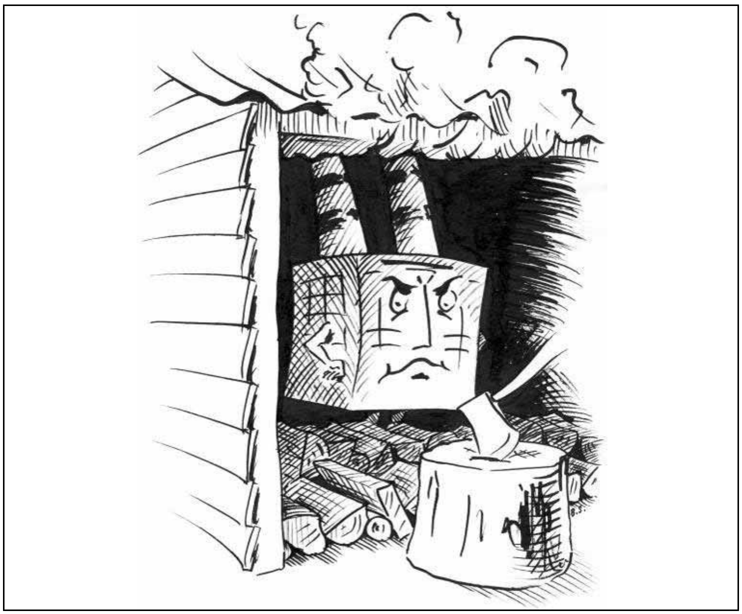

Figure 2: A power station was hiding in the wood shed

Of particular importance is the impact on national energy statistics. On 28 April 2006 the latest edition of the MED Energy Data File was released, with major changes to the residential sector use of wood fuel (see Section16).

As well as work undertaken by BRANZ on contract to commercial and government organisations, we are aware that HEEP analysis, including published reports, has been used by a number of organisations, including the Electricity Commission, EECA, Department of Building and Housing, Ministry for the Environment and energy companies.

For the first time the full HEEP Year 9 report was made available on the BRANZ website for free downloading as a PDF file. The report was released on 16 October 2005 and by 30 June 2006, 360 copies had been downloaded. Copies have been requested from 22 countries, from Australia to the United Arab Emirates, although most have gone to New Zealand (65%) followed by the United Kingdom (9%) and Australia (8%). Analysis of the reasons for downloading found 56% were to be used in work or research, while only 24% were for ‘personal interest’. Policy, product development and educational use were each around 5%, while students downloading the report for their studies was only 8%.

HEEP papers and Executive Summaries are also receiving considerable interest, with a 49% increase over the previous year – 4,700 downloads in the year to the end of June 2006 compared to 3,100 in the year to the end of June 2005.

On 16 November 2005 a 10 year celebration was held for HEEP at the Wellington Museum of City and Sea. Keynote speakers were Mr Stuart Kendon (Chairman of BRANZ Ltd), Ms Jeanette Fitzsimmons (MP, Leader of the Greens and Government spokesperson on energy efficiency) and Mr Murray Bain (CEO FRST). The theme illustrations are shown in Figure 3.

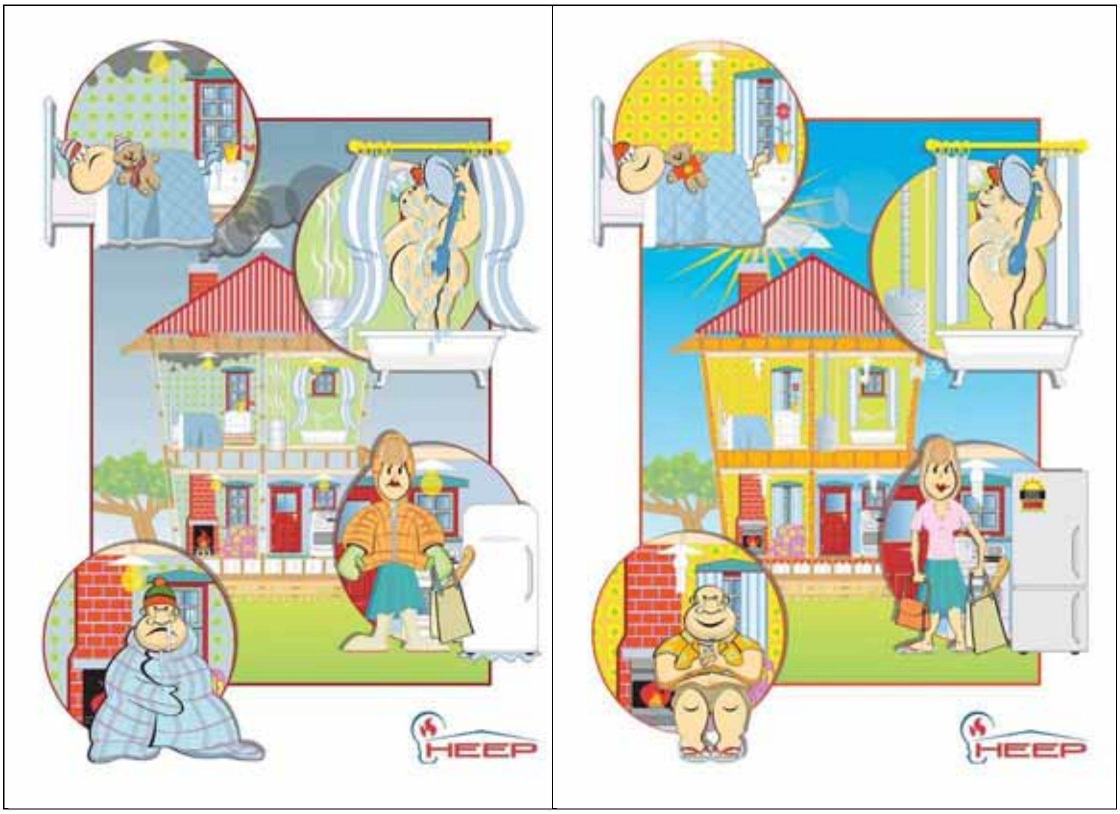

Figure 3: Theme illustrations from the HEEP Year 10 celebration

1.3 Further information

In addition to the annual reports, members of the HEEP team have regularly published results from the work, spoken at conferences in New Zealand and overseas, and provided presentations and radio and TV interviews.

Section 26 provides full references for a range of HEEP written material:

- HEEP reports
- HEEP *BUILD* articles
- HEEP conference papers
- Other HEEP references.

The results from the HEEP analysis are readily available to full financial partners, who have access to published reports before they are released to the general market and direct access to the HEEP research team. They can also discuss their specific needs with the team and how the monitoring programme can best meet their needs.

HEEP analysis is also available to other interested groups. Please contact us and we will work with you to define your question and work out how HEEP analysis could best assist you. On request, your name can be included in our email list providing HEEP results several times a year.

If you are interested in participating in any part of the HEEP work, or would like further information about obtaining outputs customised to your specific needs, please contact the HEEP team at BRANZ Ltd:

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1.4 Acknowledgements

The number of participants involved in HEEP has steadily increased over the years since the project's inception. Two research funders were involved during the entire period and their support is gratefully acknowledged:

- Building Research (BRANZ Inc)
- Foundation for Research, Science and Technology, Public Good Science & Technology Fund (PGST).

Other funders included:
The funding support of the following organisations over the life of HEEP is gratefully acknowledged:

- Energy Efficiency and Conservation Authority (EECA)
- Fisher and Paykel Appliances Ltd
- Social Policy Agency, Ministry of Social Policy, Te Manatu mo nga Kaupapa Oranga Tangata (now Ministry of Social Development, Te Manatu Whakahiato Ora)
- Cement and Concrete Association of New Zealand
- PowerCo, Wanganui
- TransAlta New Zealand Ltd, Wellington
- TransPower New Zealand Ltd
- WEL Energy Trust, Hamilton.

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- Krystle Stewart, Student, Victoria University of Wellington.

The HEEP team is also grateful to all the house occupiers who over the past 10 years have responded to our questions and permitted us to monitor their homes. Without their cooperation this research would not have been possible.

We wouild like to acknowledge our colleagues within our organisations for their support and assistance in so many, many ways.

2. ENERGY END-USES

As the monitoring has been completed for each region and the data analysed, the HEEP annual reports have included appliance energy use breakdowns. With the last monitoring completed in May 2005, and the data processed and checked, this report provides the final analysis of annual appliance energy use.

The statistical analysis was carried out by John Jowett, consultant statistician to the HEEP project. Analysis of the HEEP energy data is not a straightforward process, as the selection probabilities of the various houses and appliances need to be accounted for, as well as appropriate allowances made for missing data. Analysis of the energy use by the end-use monitored plug-in appliances is particularly involved. The analysis process is documented in HEEP internal documents. The analysis was carefully designed to avoid biased estimates (those that are systematically too high or too low) – potentially a crucial issue when undertaking random monitoring of individual appliances.

In this section the annual appliance energy use is given by end-use, fuel and location. The end-uses include: the major circuit loads including total and hot water; appliance groups (e.g. refrigeration, heating); and where there is sufficient data available, individual appliances (e.g. dishwasher, TV).

Each of the individual estimates is given as a mean (average) and standard error of the mean. The standard error indicates the accuracy of the estimate, and should be considered when using these estimates. An accuracy of ±10% was the target for HEEP for the broad level estimates of quantities such as total electricity, hot water and similar large energy uses on a nation-wide basis, and the sample size of 400 houses was chosen to achieve this (see HEEP Year 3 report, Camilleri et al 1999). This level of accuracy was achieved or exceeded for the broad level national estimates, and in some cases also for the strata (city) estimates of some individual end-uses or end-use groups.

The accuracy for many of the regional estimates is not as good as the national estimates due to the smaller sample sizes, and thus care needs to be exercised when comparing estimates between regions. If the difference between two averages is comparable to their standard errors, then there is no evidence to support a conclusion that the energy consumption is different. There may well be a difference, but its existence and direction cannot be established from the data with an acceptable level of confidence – taken here as 95% confidence level.

For example, Table 6 gives the total electricity used per occupied dwelling in Auckland (7,970±520 kWh/occupied dwelling/year) and Tauranga (7,240±850) – a difference of 730, which is similar to the standard errors. As they are not statistically significantly different, we conclude there is no difference at the 95% confidence level.

It is important to note that the difference in the size of the standard errors can be due to a range of causes, including the sample size, large variations in the behaviour of the different occupants, variation in the house heating fuel type etc.

For ease of comparison, data for all fuel types is reported in units of kilowatt-hours (kWh), where 1 kWh = 3.6 MJ. All values are gross energy unless otherwise stated.

2.1 Changes in electricity use since 1971/72

Has energy use in New Zealand households changed over time? In 1971/72 a major investigation was undertaken into the use of electricity in New Zealand homes. Electromechanical dial-type kWh meters were used to monitor the total load and the main appliances (NZ Department of Statistics 1973). A sub-set of the houses were also investigated to learn more about the importance of thermal insulation in the New Zealand climate. Temperature monitoring was limited to 'temperature-time integrators' – small coulombic cells that provided average temperatures over a two month period (NZ Department of Statistics 1976).

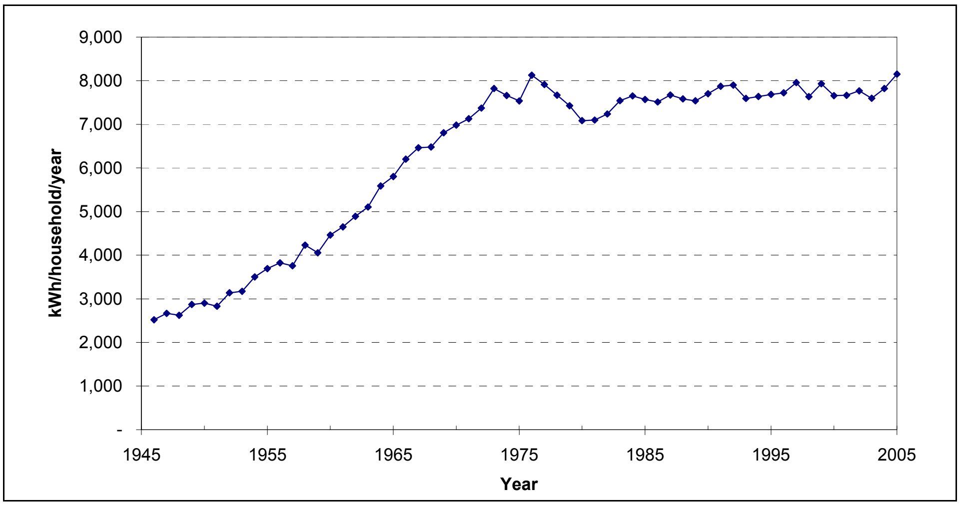

Figure 4: Electricity use per household 1946-2005[1]

The 1971/72 survey was undertaken at a time when electricity consumption had been growing rapidly since the end of World War II. Figure 4 shows this growth and the subsequent levelling off of residential electricity demand per household. In the past 35 years there have been major changes in household energy use, but the old results continue to support both Government and electricity industry policy. As the 1971/72 study monitored only electricity, the use of other fuels was left unquantified.

Figure 5 shows the breakdown in electricity end-uses from the 1971/72 study, while Figure 6 gives the breakdown from HEEP. The 1971/72 heating was estimated by comparing summer to winter electricity usage, as the plug-load heaters were not separately monitored. Although space heating remains close to the same proportion, there have been sizable changes in the importance of the other electricity uses.

The 'range' in a 1970s New Zealand home was free-standing, and often the main source of power sockets for the kitchen. The hot water jug, toaster, cake mixer and even the electric heater could be plugged in one of the two sockets. More than 30 years later the kitchen is likely to have a number of power sockets and this, coupled with an increase in factory prepared meals and snacks (e.g. biscuits are not now baked twice weekly), could have contributed to the reduced stove electricity use.

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[1] Data extracted from "Annual Statistics Relating to Electricity Generation" for appropriate years. Courtesy Dr Jonathon Lermit.

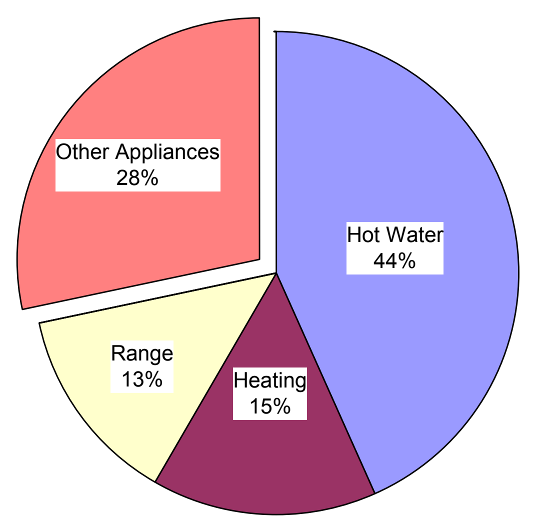

Figure 5: Electricity uses 1971/72
8,400 kWh pa

Source: NZ Department of Statistics 1973

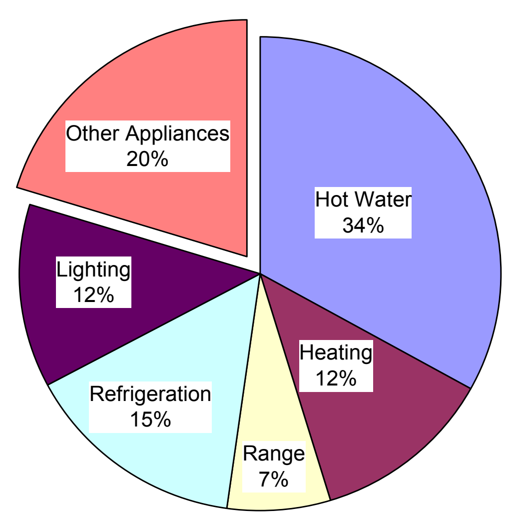

Figure 6: Electricity uses HEEP
7,240 kWh pa

Source: HEEP analysis

Water heating electric energy use has reduced, due at least in part to the increasing use of reticulated natural gas. The use of showers has changed – in 1972/72 they were occupant reported to be ‘only’ or ‘mainly’ used in 41% of households, but are now ‘mainly’ used in 94% of the HEEP houses.

It is in appliances that the greatest shift has been seen. A wider range of ‘modern’ appliances, increased lighting, new combination fridge freezers and the increased use of electronic controls (with increased standby power demand) have all played a role – one that was undetectable by simple observation or even counting of appliances. Appliances have grown from 28% to 47% of electricity consumption.

Analysis of the HEEP data has found no simple relationship between the number of electrical appliances and either the total energy or peak power demand. The use of the electrical appliances is more important than the number e.g. the second (3rd, 4th etc) TV is used far less than the main one (which is often the largest).

Other changes have also occurred in the residential sector. The average number of occupants has fallen 22%, from 3.55 per house in the 1971 Census to 2.78 in the 2001 Census (NZ Department of Statistics 1975, Statistics NZ 2002). Electricity consumption per occupant was 2,365 kWh/year in the 1971/72 survey, and is 2,690 kWh year from HEEP, while electricity use per dwelling is stable. Manufactured (town) gas is no longer made, but about 14% of houses are now on reticulated natural gas and many others use bottled LPG. Many open fires, and old solid fuel stoves, have been replaced by more modern, efficient solid fuel burners.

2.2 Energy use distribution

Although central tendency statistics (mean, median and mode) are commonly used to help understand patterns, they do not provide any guidance on the spread. A cumulative density plot provides an easy way to visualise data, and to examine the pattern of use. In particular, the percentage of households that have energy consumption that is greater or less than any given threshold can be easily seen.

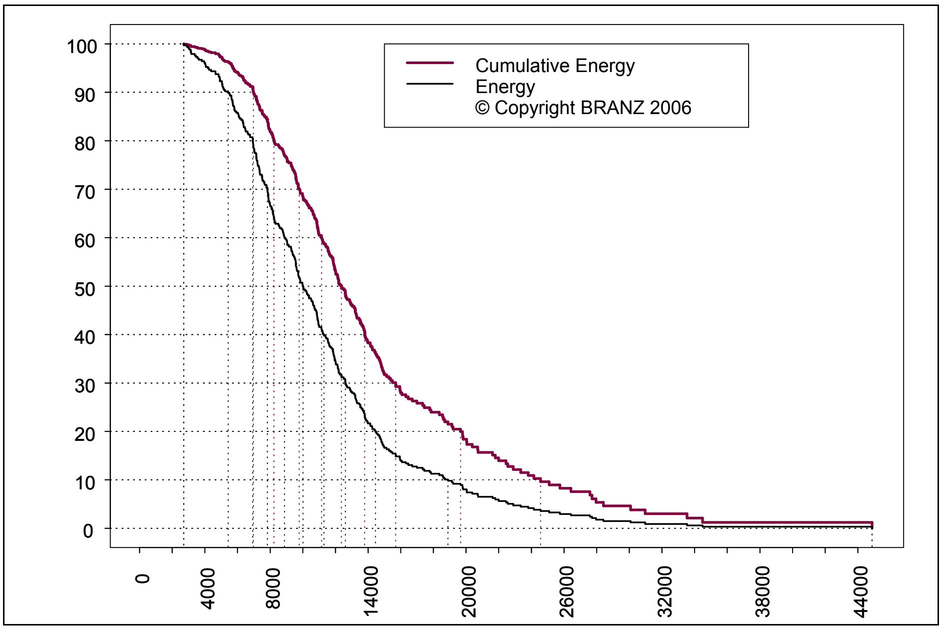

Figure 7: Energy use distribution – all fuels

Figure 7 provides two cumulative density plots on common axes. The range of household energy consumption in kWh/yr is on the horizontal axis. The heavy, topmost curve shows the percentage of total residential energy consumption used by houses at or exceeding this level of energy consumption. The lighter, lower, curve shows the percentage of houses at or exceeding this energy consumption. In both cases the relevant percentage (of total energy or households) is shown on the vertical axis.

Reference lines are drawn from the horizontal or vertical axis until they meet the relevant curve, and then traced to the other axis. For example:

- a horizontal line drawn from the 20% mark until it intersects the energy curve, then dropped vertically down to the X-axis intersect at 14,450 kWh/yr
- a vertical line up from 14,450 kWh/yr until it intersects with the cumulative energy curve, and then taken horizontally across to the Y-axis where it intersects at 36%.

Thus Figure 7 shows that the top 20% of households use more than 14,450 kWh/yr, and these households account for 36% of the energy used in all households. Conversely, the bottom 20% (80% on the Y-axis) of households use less than 6,940 kWh/yr, but they account for only 9% of the total household energy use. These results are also tabulated in Table 139.

The cumulative density plot also shows the maximum and minimum energy use for the houses monitored. In Figure 7 the maximum energy use measured is about 45,000 kWh/yr, where the line drops to 0%, and the minimum is about 2,500 kWh/yr where the line is at 100%. Since HEEP only monitored 400 houses, it is highly unlikely that either the highest or lowest energy-using household in New Zealand was monitored. The national maximum will be higher, and the national minimum lower. Thus Figure 7 maximum and minimum values are not reliable national estimates. However, statistical arguments suggest that, with a 95%

confidence, less than 0.75% of houses fall outside the observed range of 2,500 kWh/yr to 45,000 kWh/yr.

In practical terms there will always be a few houses that use no energy at all for a particular end-use. For example, there are houses in New Zealand that have no electricity supply, and houses with no hot water service of any type. In terms of the maximum, there is no practical maximum. There may also be some VERY large houses in New Zealand using HUGE amounts of energy e.g. over 100,000 kWh/yr – we just didn't find them in HEEP as they are very rare. It might be possible to track down these houses through power company records. Large 'mansions' with indoor heated swimming pools, spa pools and air-conditioners are the types of houses that could be expected to have such high energy consumption.

Table 2 provides information on the highest and lowest 20% for total fuels and separately for electricity, gas, LPG and solid fuel. The total and the individual fuels demonstrate skewed distributions, with high users consuming more per house than the smaller users. The ratio of the energy use per house for the top 20% of houses to the bottom 20% of houses ranges from 2.1 to 12.8.

Figure 7 and Table 2 suggest that for a goal of reducing total household energy use (i.e. energy conservation), it is likely that the largest absolute reductions will come from the high energy using top 20% of houses.

Fuel	**Bottom 20%**		**Top 20%**		**Ratio Top: Bottom**
	Use under:	**% of energy**	**Use over:**	**% of energy**	
Electricity	4,860 kWh/yr	10%	10,380 kWh/yr	35%	2.1
Gas	2,580 kWh/yr	5%	9,900 kWh/yr	34%	3.8
Solid fuel heating	450 kWh/yr	1%	5,740 kWh/yr	57%	12.8
LPG heating	180 kWh/yr	3%	1,110 kWh/yr	50%	6.2
All fuels	**6,940 kWh/yr**	**9%**	**14,450 kWh/yr**	**36%**	**2.1**

Table 2: Fuel use – top and bottom 20%

The following four figures provide energy and cumulative energy density curves for:

- Figure 8: electricity
- Figure 9: gas (mains natural gas and large cylinder LPG)
- Figure 10: small cylinder LPG (free standing, unvented, LPG heaters)
- Figure 11: solid fuel (including wood and coal).

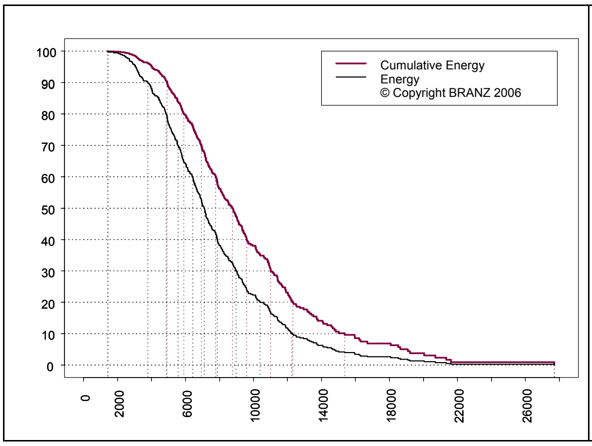

Figure 8: Energy use distribution – electricity

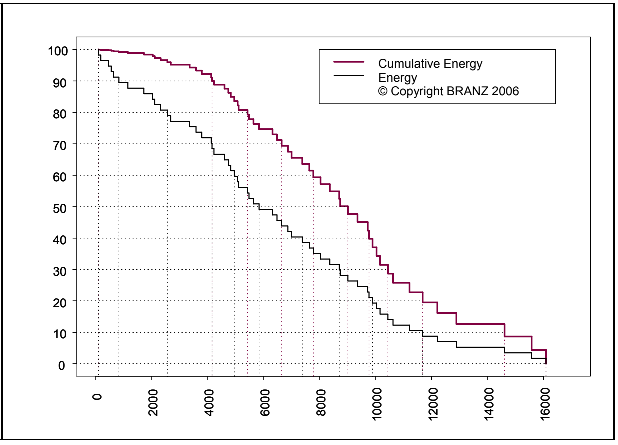

Figure 9: Energy use distribution – gas (natural gas & large bottle LPG)

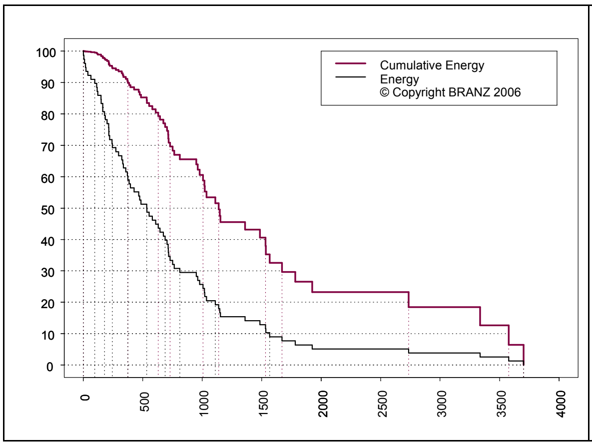

Figure 10: Energy use distribution – LPG (small bottles)

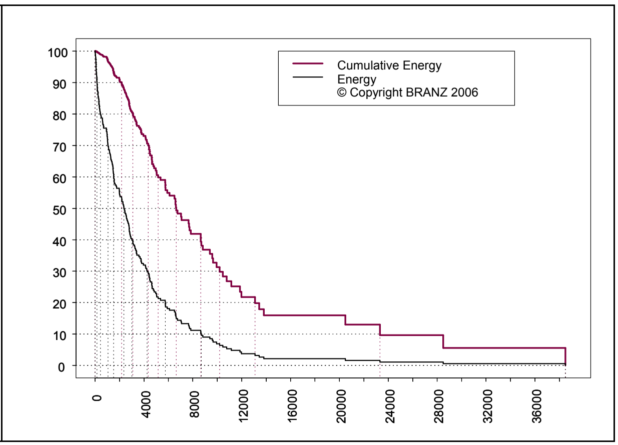

Figure 11: Energy use distribution – Solid fuel

2.3 Patterns of energy use

Although the average energy use for a given fuel or end-use provides a quick overview, it can disguise the actual use if it occurs only in a limited number of houses. For example, if one house out of 100 uses 100 units of a fuel, but the other 99 do not use that fuel at all, then the average use is 1 unit – which although a useful number, is not meaningful. Table 3 provides an estimate of circuit energy loads for houses that have that fuel end-use i.e. not averaged over all houses.

Isaacs et al 2003 (Section 4.2) provided preliminary analysis of the proportions of energy (electricity and natural gas only) by end-use for Auckland, Hamilton, Wellington and Christchurch. With the completion of the monitoring, data analysis has been completed for all fuel types. It has been found that for some end-uses, the household use variability makes it impossible to provide a detailed regional breakdown. This issue can only be resolved with a larger scale, or more detailed regional monitoring programme than was possible with HEEP.

Description	Annual kWh	Standard error
Total – reticulated gas	6227	189
Range – electricity	536	57
Range – reticulated gas	706	63
Range – solid fuel	942	69
Night store – electricity	2198	112
Fixed wired – electric heating	860	124
Open fire – solid fuel	886	105
Heating – reticulated gas	4204	192
Heating – LPG	746	90
Other heating – solid fuel	4446	217
Heating – oil	1188	1306
Large miscellaneous – electricity	2065	154
Spa – electricity (circuit)	1986	146
Small miscellaneous – electricity	28	13
Hot water – electricity	2778	114
Hot water – reticulated gas	5338	146
Wetback – solid fuel	908	100
Hot water – oil	3348	1674

Table 3: Energy end-use by fuel for houses with that end-use

Note: Standard Error of the mean (SE) are estimated.

Total energy and electricity use appears to vary little by region, although on a per occupant basis a different picture emerges. The reason for this might be due to the increased use of solid fuel heating in the colder parts of New Zealand.

Figure 12 provides an overview for all fuel types of the different energy end-uses. The locational variables are discussed in Section 1.1. As would be expected, Figure 12 shows that in the cooler regions (Dunedin/Invercargill cool clusters) space heating is close to half of the total energy use. In the warmer areas, water heating is the largest single energy use.

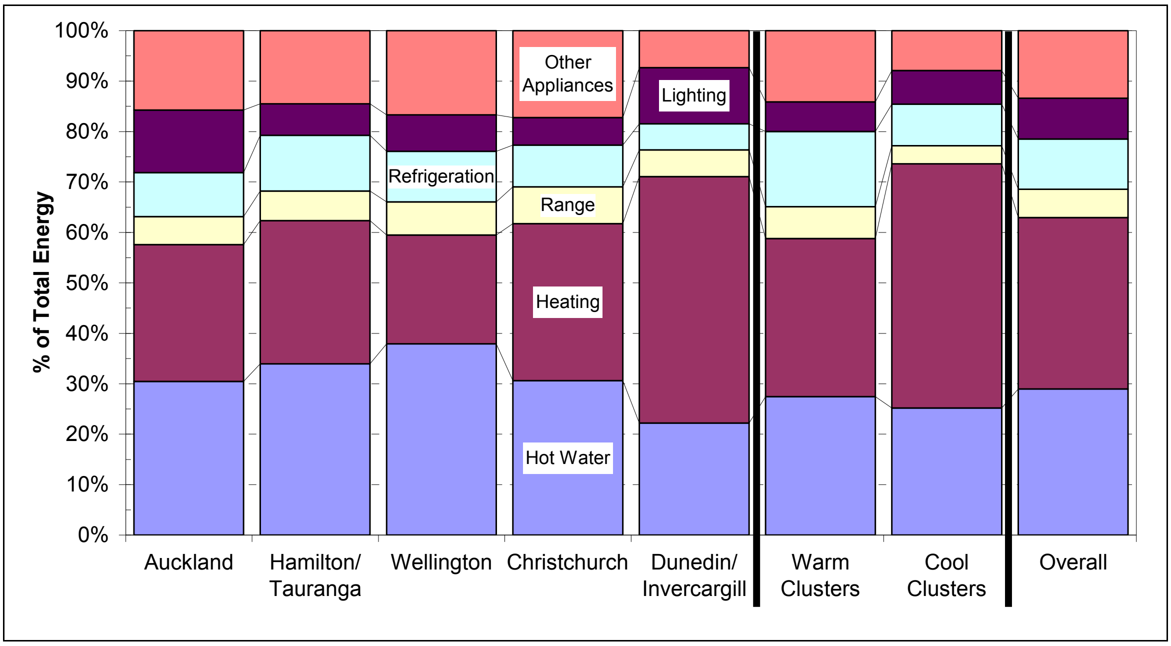

Figure 12: Regional patterns of energy end-uses

The total annual energy consumption for all fuels is given in Table 4 on a national and regional basis. The national average is 11,410 kWh per year. Note that the differences between most of these locations are not statistically significant. This does not necessarily mean that there is no difference, but simply that the estimate precision is insufficient to establish whether a difference exists or, if so, its direction.

Location	Average energy use (kWh/occupied dwelling/year)	Standard error
National (Cities and Clusters)	**11,410**	**420**
Auckland	10,660	520
Hamilton/Tauranga	10,750	840
Wellington	10,860	790
Christchurch	11,010	750
Dunedin/Invercargill	14,580	1,450
Clusters	**11,740**	**810**
Warm clusters	9,960	790
Cool clusters	13,780	1,170

Table 4: Total annual energy consumption – all fuels

When the number of HEEP occupants is taken into account a different picture emerges. Table 5 shows that there is higher energy consumption per person in the locations with colder climates, and less for those in warmer climates, and these differences are statistically significant for most locations. Auckland has the highest average number of occupants at 3.34 per occupied dwelling, and it appears plausible that this has the effect of increasing the total annual energy consumption in Table 4.

Location	Number of occupants	Average energy (kWh/occupant/yr)	Standard error
National	**2.90**	**3,930**	**140**
Auckland	3.34	3,190	210
Hamilton/Tauranga	2.33	4,610	440
Wellington	3.00	3,620	280
Christchurch	3.00	3,670	290
Dunedin/Invercargill	2.65	5,500	620
Clusters	**2.86**	**4,100**	**300**
Warm clusters	3.00	3,320	230
Cool clusters	2.70	5,100	450

Table 5: Total annual energy consumption per person – all fuels

Table 6 shows the results are similar when only electricity is considered. The national average annual electricity consumption is 7,800±420 kWh per year. In most locations, the electricity use is not statistically significantly different, meaning that regional differences cannot be held to have been established (with the possible exception of Dunedin/Invercargill).

Location	Average electricity (kWh/occupied dwelling/year)	Standard error
National	**7,800**	**420**
Auckland	7,970	520
Hamilton/Tauranga	7,270	840
Wellington	7,840	790
Christchurch	8,710	750
Dunedin/Invercargill	10,610	1,450
Clusters	**7,300**	**810**
Warm clusters	6,740	790
Cool clusters	7,950	1,170

Table 6: Total annual energy consumption – electricity only

Scaling by the average number of occupants changes the results (Table 7), and now there are statistically significant differences between various locations, with a general trend for higher electricity consumption per person in colder climates.

Location	**Number of occupants**	**Average electricity (kWh/occupant/year)**	**Standard error**
National	**2.90**	**2,690**	**140**
Auckland	3.34	2,390	160
Hamilton/Tauranga	2.33	3,120	350
Wellington	3.00	2,610	260
Christchurch	3.00	2,900	240
Dunedin/Invercargill	2.65	4,000	620
Clusters	**2.86**	**2,550**	**260**
Warm clusters	3.00	2,250	220
Cool clusters	2.70	2,940	410

Table 7: Total annual energy consumption per person – electricity only

The HEEP breakdown of New Zealand household energy consumption by fuel type is given in Figure 13. Electricity use accounts for 69% of total residential national fuel use, followed by solid fuel at 20%, reticulated gas at 9% and bottled LPG at 2%. Heating oil is used in very few houses. The breakdown by location varies greatly, depending on the types of fuels that are used in houses, particularly for space heating. Many locations do not have a reticulated gas supply, and other fuels are used instead for space heating, cooking and water heating.

The HEEP breakdown of New Zealand household total energy consumption by end-use is given in Figure 14. The largest portion is space heating at 34%, then hot water at 29%, and refrigeration, other appliances, lighting, and range at around 10% each. The proportions vary by location, with less space heating energy used in warm and more in colder climates – up to 70% of energy use in the coldest climates.

Combining water and space heating, Figure 14 shows that on average that just under two-thirds (63%) of household energy use is for low grade heat (less than 100°C).

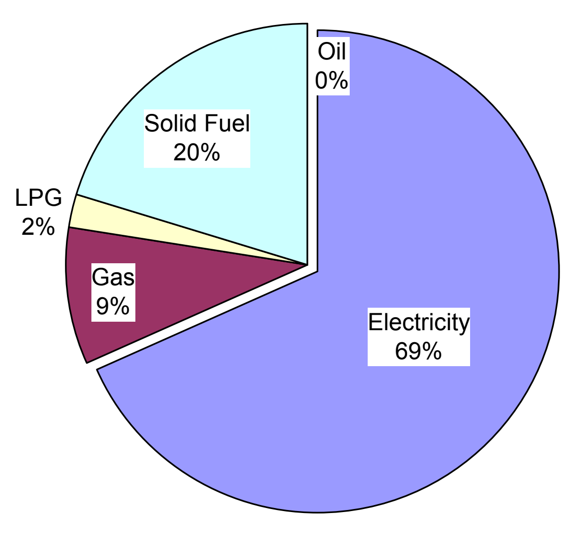

Figure 13: Total energy use by fuel type

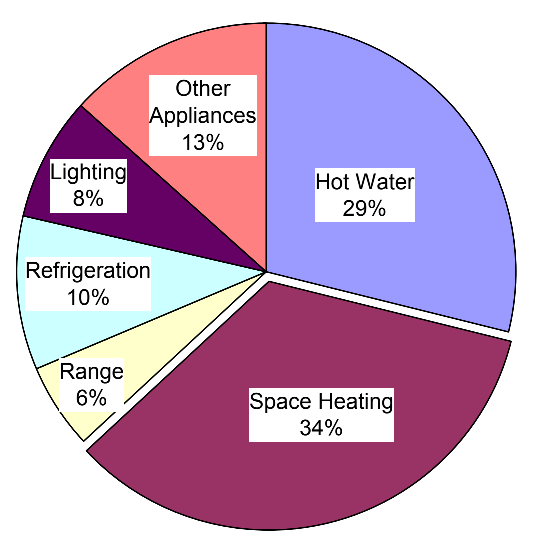

Figure 14: Total energy use by end-use

Figure 15 provides an overview of the relative importance of the major heating fuels based on the gross energy. Figure 16 makes conservative allowances for the efficiencies of different appliances – while 100% of electricity is converted to heat, a reasonable quality enclosed solid fuel burner would convert 60% of wood into heat.

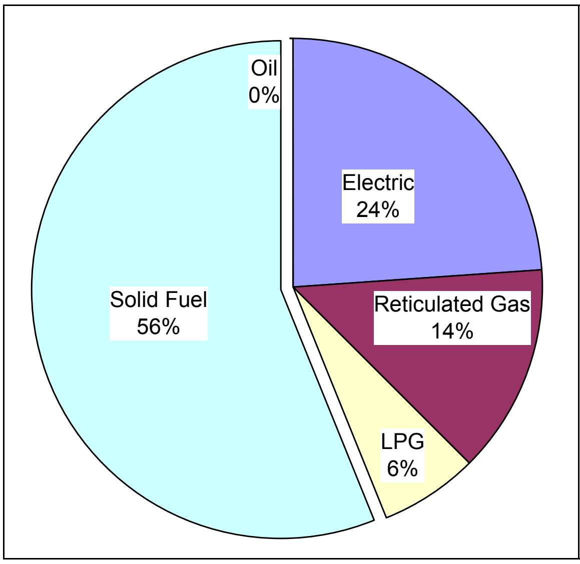

Figure 15: Space heating gross energy by fuel

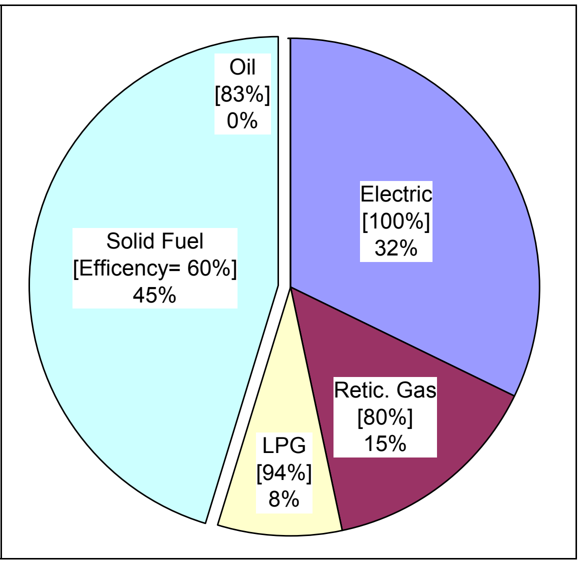

Figure 16: Space heating delivered energy by fuel

Figure 15 shows that solid fuel is the most important heating fuel with about 56% of gross[2] space heating, followed by electricity at 24%, reticulated gas at 14%, LPG at 6% and oil under 1%. After allowances for conversion efficiency (in square brackets [ ]), Figure 16 shows that the proportions change, but solid fuel remains the most important space heating fuel in New Zealand dwellings. Heat pumps (which produce more heat output than electricity use) are currently found in very few houses.

The relative importance of the different space heating fuels varies by location. In the clusters (selected from locations with a population of less than about 50,000), which represent half of New Zealand's population, about 77% of space heating gross energy consumption is supplied by solid fuel and only 10% by electricity. In the clusters in cooler climates this is even more pronounced, with 81% of gross space heating supplied by solid fuel. Of the cities, Christchurch had the highest percentage of solid fuel use, at 54% of gross space heating energy use.

Appendix 2: Energy Consumption Tables provide HEEP estimates of average annual gross energy use for total energy, hot water, space heating and selected appliances. Due to the small sample size, fuel oil is not separately reported. The tables provide analysis for the national and locations as described in Section 1.1:

- Table 186: the average total energy use per house for all fuels, electricity, gas, LPG and solid fuels
- Table 187: the average annual hot water energy use by house for all fuels, electricity, gas and solid fuels
- Table 188: the average annual space heating energy use by house for all fuels, electricity, solid fuels, gas and LPG
- Table 189: the average annual energy use per house for all cooking, range, lighting and refrigeration.

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[2] Gross energy is the energy content of fuel before it is used in a heating appliance. Solid fuel and gas burners have efficiencies under 100% – some energy is lost during burning and only part is released as heat to the room. Typically gas burner efficiency is about 80%, and solid fuel burners 50-70% e.g. for approval in Christchurch clean air zone 1, over 65% heating efficiency is required (see www.ecan.govt.nz).

These tables provide the average over all houses in the location (national or regional) – NOT the average use in houses that use that particular fuel or end-use. For example, for Table 186 (average total energy use) 100% of HEEP houses used electricity, 17% gas (mains natural gas or large cylinder LPG), 32% LPG (small 9 kg cylinders) and 55% solid fuel.[3]

2.4 Energy consumption over the year

Household energy consumption varies seasonally, most noticeably with increased space heating, hot water heating and lighting during the winter months. Total energy consumption (all fuels) rises by a factor of nearly three times from summer to winter. Most of this increase is due to space heating, which is very low in the summer months but rises (on average) to 280 kWh per month in July. Range energy use increases by about 50% from summer to winter, lighting by about 2.5 times, and hot water by about 60%.

It is expected that space heating energy use will increase due to colder temperatures, peaking in the coldest month (July), as shown in Figure 17. The response of the other energy uses is not so clear. Why should range energy increase by 50% in winter? Why should average water heating energy use increase by 60%?

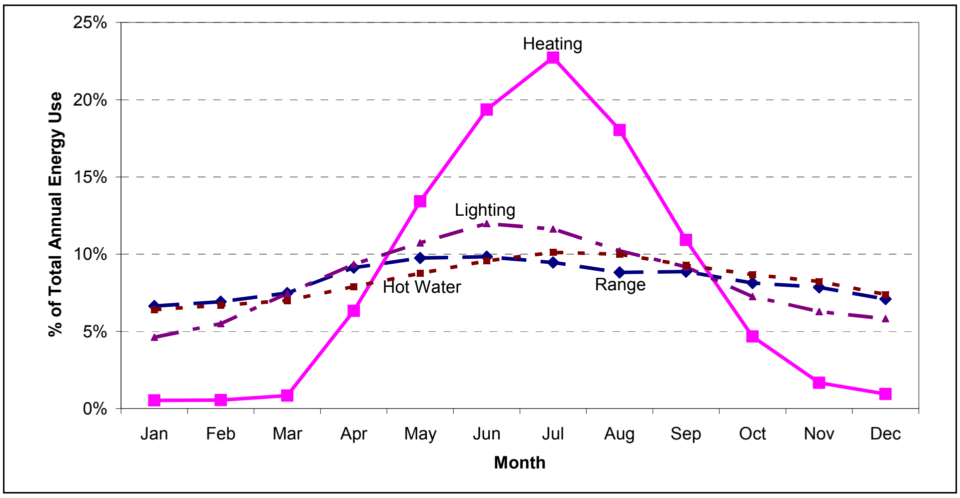

Figure 17: Energy use by end-use and month

It will take a little more energy to heat food or water from lower winter temperatures, but most of the increase must be due to changes in cooking habits – more range use means cooked meals, and these are more common in the cooler winter months (just as BBQ meals are more common in the warmer summer months).

Lighting energy use increases due to shorter daylight hours, and peaks in June (the month with the shortest day), a month earlier than heating. Hot water energy use increases markedly in winter, with some of the increase due to colder water temperatures (more energy is needed to heat the colder water) and higher standing and pipe losses due to cooler indoor air temperatures. These effects might account for about a 20% increase in hot water energy consumption. Behavioural changes might account for the rest – perhaps longer showers to compensate for colder weather, or perhaps more clothes washing and drying.

The summer months of December, January and February include summer holiday periods, and for many households there will be a period of vacation, often of several weeks. February energy consumption is perhaps most typical of summer energy consumption for most

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[3] Solid fuel is used in: enclosed solid fuel burner; open fire; solid fuel burner with wetback water heating; chip heater; solid fuel hot water cylinder; or wood/coal range.

households, but in most cases the February energy use is very close to the January one. There could be a number of possible reasons for this e.g. retired people taking their extended summer holidays in February.

2.5 Appliance electricity use

Table 8 lists the different energy end-uses monitored in the HEEP houses, and the titles under which they are amalgamated into a smaller number of functionally similar groups. It should be noted that the ‘Large miscellaneous’ and ‘Small miscellaneous’ appliance groups include wide ranges of disparate end-uses, any one of which may only be found in a limited number of households.

Group	End-use	Group	End-use
Entertainment	Computer Computer + access DVD Games console Sky/Saturn decoder Stereo Television TV and video Video	**Other climate control**	Cupboard heater Electric blanket Extractor fan Fan Heated towel rail Heat lamp Rangehood Ventilation system Waterbed
Heating & cooling	Heat pump Ceiling heater Central heating Dehumidifier Gas heater controller Heater Night store heater Underfloor heating	**Other cooking**	Bench top oven Blender Bread maker Crockpot Deep fryer Electric coffee maker Frying pan Juicer Sandwich maker Toaster
Large miscellaneous	Arc welder Electric water pump Pool pump Sauna Spa bath Spa pool	**Small miscellaneous**	Electric fence Espresso machine Iron Kiln Oxygen machine Security system Sewing machine Vacuum cleaner Waste disposal
Lighting	Portable lamp Lights		
Refrigeration	Freezer Fridge Fridge freezer		

Table 8: Appliance groups

The HEEP study included measurements of the energy consumption of individual electrical appliances. One, two or three individual appliances were monitored each month in the 100 end-use monitored houses (i.e. one in four of all HEEP monitored houses). Due to the many different types of appliances and the limited monitoring equipment available, for some appliances only a few (or sometimes none) were monitored in each location. As a result, the coverage of individual strata (cities) or cluster (outside major cities including rural) locations is not adequate to separate them out for comparison. However, nation-wide figures have been calculated by individual appliances.

The average electricity consumption per house for the various appliance types is given in Table 9. This is the consumption for each appliance type or group, on a per house basis, so for example the ‘Entertainment’ group includes all TVs in the houses (see also Table 8 for more detail on the appliance groups). The larger electricity uses of hardwired lighting, hardwired range and refrigeration are reported separately (see Figure 6).

Appliance type	Average (kWh/year)	Standard error
Computer/games	227	43
Dishwashers	107	18
Dryers	119	23
Electric jug	152	12
Entertainment	364	57
Large miscellaneous	73	58
Microwave	62	6
Other climate control	119	70
Other cooking	52	8
Small miscellaneous	40	9
Spa pools	123	52
Washing machines	63	12
Lighting (hardwired)	915	87
Range (hardwired)	497	42
Refrigeration	1,119	72

Table 9: Average appliance electricity consumption per household

For some appliances enough data was collected to provide estimates per appliance. Note that the standard error is only an estimate, as for technical reasons it is very difficult (or in some cases, impossible) to calculate a valid standard error.

The 'per appliance' estimate is also difficult to interpret as there may be more than one of that appliance in a house, but one or more may be virtually unused. Notable examples are plug-in lighting, heaters and 'Other entertainment' appliances. Appliances that were stated by the occupants to be never used were generally not monitored and are not included in the averages. However, some monitored appliances never recorded any power consumption. The HEEP focus was on per household energy use; use 'per appliance' may not always be a meaningful concept.

Appliance	Average (kWh/year)	SE	Appliance	Average (kWh/year)	SE
Computer/games	196	27	Lighting (plug-in)	40	10
Dehumidifier	554	281	Microwave	78	5
Dishwasher	211	28	Other climate control	289	105
Dryer	173	32	Other cooking	19	6
Electric blanket	49	9	Other entertainment	114	23
Electric jug	157	12	Range hood	27	7
Portable heater	71	64	Refrigerator	367	62
Freezer	663	39	Small miscellaneous	4	2
Fridge freezer	621	30	Spa	398	288
Heater	488	81	Toaster	20	3
Iron	11	2	TV	132	13
Large miscellaneous	116	57	Vacuum cleaner	21	4
			Washing machine	59	7

Table 10: Average electricity consumption per appliance

Figure 6 (Section 2.1) provides a breakdown of average electricity use, showing that the 'Other Appliances' grouping accounts on average for 20% of HEEP household electricity use. This 20% is further analysed in Figure 18 and Table 11 below.

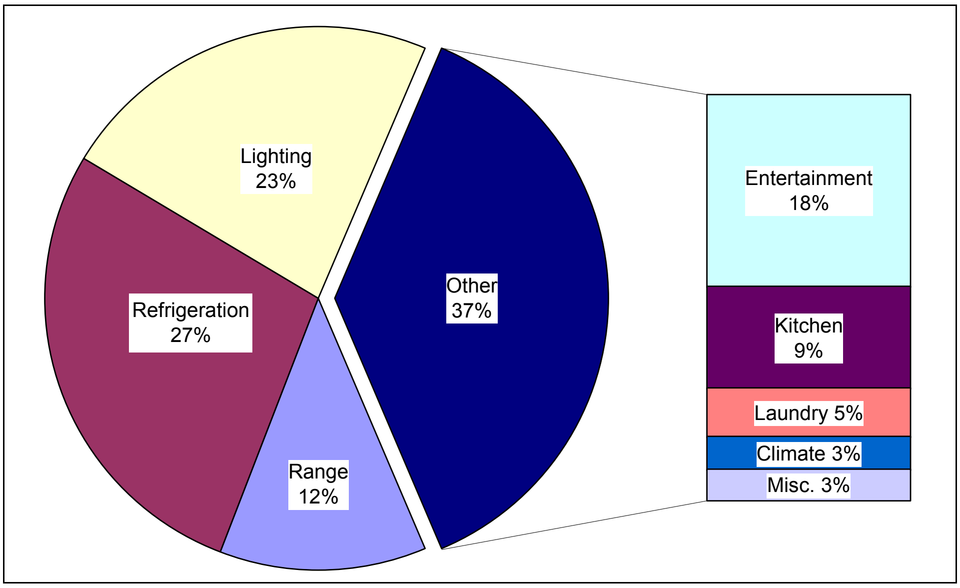

Figure 18: Electric appliances

Broad category	Electric appliance groups included:	Other appliance %	Electric appliance %
Entertainment	Entertainment, computer/games, spa pools	48%	18%
Kitchen	Dishwasher, other cooking, electric jug, microwave	25%	9%
Laundry	Dryer, washing machine	12%	5%
Climate	Other climate control	8%	3%
Miscellaneous	Small, large	8%	3%
Larger load	Lighting (hardwired)		23%
Larger load	Refrigeration		28%
Larger load	Range (hardwired)		12%
	TOTAL	**100%**	**100%**

Table 11: Average appliance category proportion of electricity

Table 11 and Figure 18 show that in the average home, the three larger loads (lighting, refrigeration and range) account for 63% of the non-spacing heating or water heating electricity use. Of the remaining appliances, the entertainment category is the next largest user of electricity. The 'Other Appliances' group includes a large number and variety of appliances, suggesting that any electricity efficiency or conservation activity will need to be well focused to achieve real benefits.

2.6 Lighting

Lighting energy use provides a variety of benefits in houses. As well as allowing activities to be carried out when there is no sunlight, it is also used for security in parts of the house in common use but lacking good daylight, and in dark spaces such as cupboards that are infrequently used.

Figure 19 illustrates that average fixed wired lighting power demand varies over the year, with the highest lighting energy load occurring during the winter months (June and July).

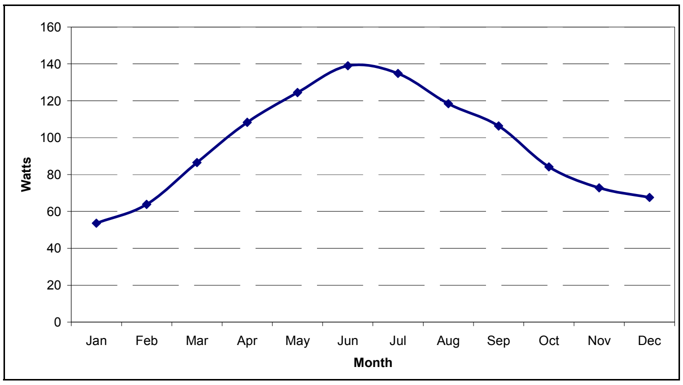

Figure 19: Average monthly lighting power – all NZ

Table 12 provides a regional breakdown of lighting power demand. Lighting energy use was collected only in the end-use monitored HEEP houses (one in four houses), and is highly variable between houses, so the standard errors are quite high. The power demand in most locations is not statistically significantly different from the national average, and only Auckland stands out. It would be expected that the further south (and hence the longer the winter evenings), the higher the winter lighting energy use would be. However, this effect cannot be proven from the monitored HEEP data. The main drivers of lighting energy consumption are the number of occupants and the floor area (see Table 120 and associated text).

Location	Annual average Watts	Standard error
Auckland	167	34
Hamilton	100	19
Wellington	101	29
Christchurch	60	15
Dunedin/Invercargill	177	17
Warm clusters	64	13
Cool clusters	80	17
All New Zealand	**104**	**10**

Table 12: Lighting power by region

2.7 Changing official New Zealand energy statistics

Figure 13 (Page 15) showed that based on the HEEP monitored data, electricity accounts for 69% of total residential national fuel use, followed by solid fuel at 20%. This new estimate is based on all HEEP data, and replaces the estimate given in the HEEP Year 9 report (Isaacs et al 2005) that solid fuel was over 15%. It was pointed out in the HEEP Year 9 report that this value differed significantly from the national energy statistics published by the MED for the residential sector.

Figure 20 (for 2004) and Figure 21 (for 2005) are calculated from the published MED Energy Data File (MED 2005, MED 2006). The ‘Other’ category includes geothermal and solar.

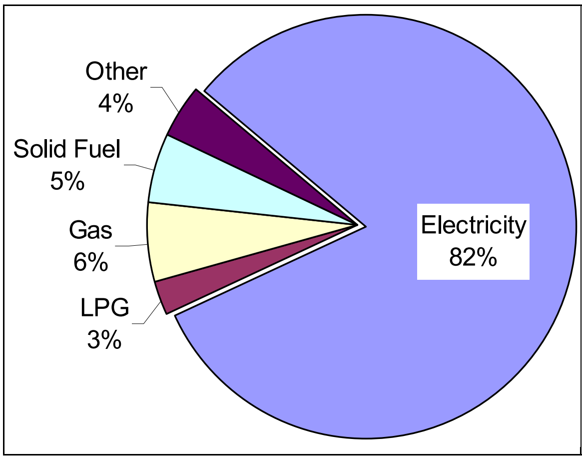

Figure 20: Fuels all end-uses (Dec yr 2004)

Source: MED 2005

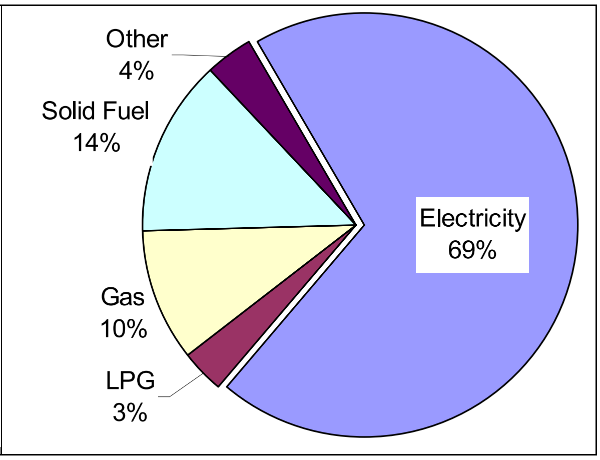

Figure 21: Fuels all end-uses (Sept yr 2005)

Source: MED 2006

Figure 20 shows the official estimate for wood and coal ('Solid fuel') used in the December 2004 year was 5% of total residential energy use. For Figure 21 it has increased to 14% – but this is not due to an increase in the actual residential use of wood or coal. The difference is explained in the supporting text (MED 2006 189-90): [4]

> *In previous editions of the Energy Data File the figures for residential wood use included in the Energy Balances were based on an average use of 4.3 GJ per household using firewood. This figure had been estimated by an industry analyst in 1996. The 'Household Energy End-use Project' (HEEP) carried out by BRANZ monitored actual firewood use and reported average annual use of 13.7 GJ.*
>
> *Due to the BRANZ figure having more validity than the earlier figure, values published in this edition have been re-calculated using this new figure.*

This result of the HEEP research has led to a reported national increase in wood use of 5.6 PJ – equal to a 1% increase in total observed consumer energy, or a 9% increase in residential sector consumer energy.

If this wood was burnt in solid fuel burners with an efficiency of 50%, it would be equivalent to a 530 MW thermal power station feeding conventional resistance heaters or a 180 MW station feeding heat pumps. For comparison, the Huntly power station is 960 MW.

In energy terms, this heating load would be a 6% increase in residential sector electricity demand if used in conventional resistance heaters, or 2% if used in heat pumps (COP 3).

The under-estimate of solid fuel use in the residential sector has critical implications for assumptions relating to the services it provides. Solid fuel is principally used for space heating, although as noted earlier in some houses it also provides a significant proportion of hot water (about 5% of all hot water energy consumption).

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[4] Available at www.med.govt.nz/templates/MultipageDocumentTOC____15181.aspx#.

3. HOUSEHOLD SELECTION

This section provides a background to the HEEP house selection methodology, and analysis of the participation rate.

3.1 Sample size

The sample size for a representative national sample was set out in the HEEP Year 2 report (Bishop et al, 1998), and the reasons for it summarised in the HEEP Year 5 report. (Stoecklein et al, 2001). It was determined that approximately 400 households should be monitored, based on analysis of data from pilot monitoring. This sample size was set so that space heating energy could be estimated with an error of less than 10% and with 90% confidence, with some spares should any houses pull out. This error target has been broadly been met on a national and sometimes regional basis.

3.2 Methodology

3.2.1 Sample Selection

The method of selecting households was first outlined in the HEEP Year 5 (Stoecklein et al, 2001) and HEEP Year 3 (Camilleri et al, 2000) reports.

Statistics New Zealand was commissioned to provide a set of randomly selected (on a population weighted basis) area units, and the HEEP team carried out further random sampling of meshblocks and then households within these.

Note: an area unit is a single geographic entity with a unique name referring to a geographical feature. Area units of main or secondary urban areas generally coincide with suburbs or parts thereof. Area units combine a number of meshblocks, which are the smallest areas used by Statistics New Zealand.[5]

The HEEP random house selection approach included the following steps:

a) Select locations. Define locations by matching them to area unit boundaries.
b) Determine household populations in selected locations, with proportions of national total.
c) Draw proportional random samples of meshblocks from selected locations.
d) Select a random household in each selected meshblock and obtain consent from residents. If no consent is given, repeat procedure within the meshblock until a house is found. If no additional house is available in a given meshblock (e.g. due to very small numbers of households), then randomly select another meshblock in that area unit and repeat the process.

A total of 399 households are included in the HEEP database. This population weighted sample includes 221 households from the cities of Auckland, Manukau, North Shore, Waitakere, Tauranga, Hamilton, Wellington, Upper Hutt, Lower Hutt, Porirua, Christchurch, Dunedin and Invercargill. The remaining 178 households were selected from 19 area unit clusters drawn at random from area units outside those cities. Eight, nine or 10 houses were randomly selected within each cluster.

Statistics New Zealand does not provide street numbers for houses within a meshblock so these had to be found from other sources. Initially for the selections in Wellington, Porirua, Lower Hutt and Upper Hutt, the council provided lists of the houses within each meshblock,

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[5] For further information see www.statistics.govt.nz under ‘Statistical methods’ then ‘Classifications’.

aided by the use of aerial photographs to identify vacant sections. For the following years, Quotable Value New Zealand (a state-owned enterprise that provides a national property valuation service) was contracted to provide the household names (owners) and addresses for the selected meshblocks.

The Local Government (Rating) Act 2002 came into force on 30 April 2003 and increased restrictions on access to owner/occupiers' names and addresses. Consequently, in 2004 Quotable Value were unable to provide the physical address of the households, but were limited to providing the name of the house owner and a postal address. This made it more difficult to follow up householders who did not reply to the initial letter, particularly in rural areas using Post Office (PO) boxes or rural delivery (RD) numbers.

3.2.2 Recruiting houses

To recruit households, an information pack was mailed containing information on the study, a freepost reply envelope, and an 0800 number for occupants to call to reply or obtain further information on the research. If no reply was received from a selected household, local field staff would phone or visit the household in person during the day or evening. If no-one was home, a further letter was left. Some households proved impossible to contact, so after three unsuccessful approaches, the house was deemed not wishing to participate. In some areas, first contact was made through a personal visit from a local resident employed by BRANZ instead of BRANZ staff.

Four households (five after 2001) were initially selected from each meshblock to allow for refusals. To prevent additional selection bias, these households were only accepted in the order in which they were selected. For example, if House 2 replied 'yes', it was not accepted for monitoring until House 1 had replied 'no' or had been excluded due to unsuccessful contact attempts.

For the selections up to 2001 (Wellington, Hamilton and the first year from Auckland, Manukau, North Shore and Waitakere), if none of the initial four households wished to participate in the survey then a replacement meshblock was selected and another four households were approached, and so on. A total of 164 meshblocks were approached to find the 106 households.

After 2001, the selection procedures were changed so that if a household was not found amongst the first five houses, then additional households were randomly selected from the same meshblock. Only where the meshblock contained a small number of houses and a majority of the households in the meshblock had been approached was a replacement meshblock selected. A total of 13 replacement meshblocks were required to select the 293 households after 2001.

A small incentive was offered. At the installation of the monitoring equipment, the house occupants received a gift of $50 and a copy of the BRANZ book *Maintaining Your Home*. The occupants received a written report of energy use in their own house after the monitoring finished (e.g. energy consumption by different appliance, peak energy use, time etc.). No information was provided to the house occupants on the results of the monitoring during the monitoring period.

3.3 Participation rate

A total of 1687 households were approached in order to select the 399 houses in the survey, giving an overall participation rate of 24%.

The participation rate for both selecting a new meshblock after four 'nos' were encountered (24%) and continuing to select houses from the same meshblock (23%) were similar. The following discussion considers the two replacement methods together.

Figure 22 graphs the frequency of the number of households that had to be approached before encountering a household that was willing to participate in the study. The higher frequencies of around 10-13 households could possibly be explained by the use of replacement meshblocks. The first replacement method would replace meshblocks once eight or 12 households had declined to take part. Under the second replacement method, replacement of the meshblock was much less common but the most frequent number of houses contacted before the meshblock was replaced was 10. The case which required 30 households to be contacted before one agreed to participate (on the far right of Figure 22), resulted from 25 'no' responses before a second meshblock was selected.

The 'expected' curve shown in Figure 22 is the distribution that would be expected if each household approached had the same probability (taken as the observed participation rate) of agreeing to take part in the study, and shows a good agreement with experimental results.

Table 13 gives a cumulative total from the expected curve and shows that theoretically it could be expected that 74% of households would be found from the initial selection of 5 households, with 93% of households being selected once 10 houses had been contacted.

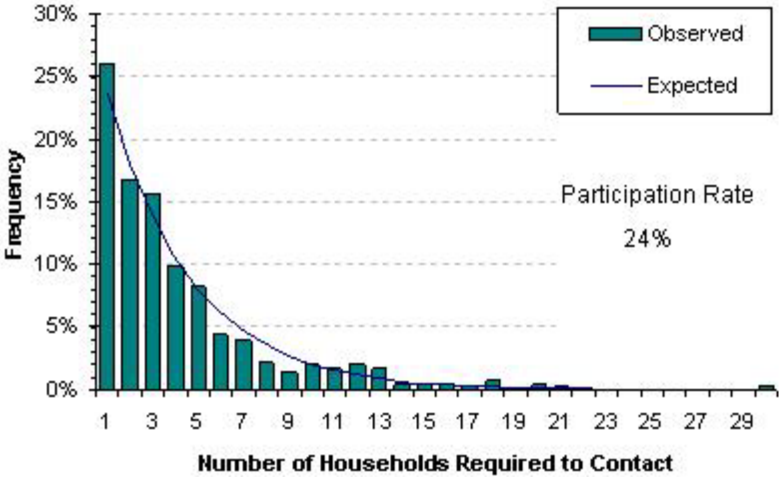

Figure 22: Participation rate of households taking part in HEEP

Households Approached	Cumulative Participation Rate
1	24%
2	42%
3	55%
4	66%
5	74%
6	80%
7	85%
8	88%
9	91%
10	93%

Table 13: Participation rate

Table 14 provides a breakdown of the participation rate for each region/cluster ordered by those most willing to take part in the study. Figure 23 graphs this data by urban level (Statistics NZ classification of the region or cluster).

Region / Cluster	Urban Level	# Households Required	# Households Contacted	Participation Rate
Wairoa	Minor Urban	9	15	60%
Arapuni	Rural etc	10	25	40%
Foxton Beach	Minor Urban	10	26	38%
Minden	Rural etc	10	26	38%
Kaikohe	Minor Urban	10	27	37%
Kamo West (Whangarei)	Major Urban	10	29	34%
Sherwood Rise (Whangarei)	Major Urban	10	31	32%
Seddon	Rural etc	9	28	32%
Invercargill	Major Urban	6	19	32%
Hamilton	Major Urban	17	54	31%
Oamaru	Secondary Urban	10	32	31%
Wellington	Major Urban	41	134	31%
Dunedin	Major Urban	14	47	30%
Tauranga	Major Urban	9	32	28%
Wai-iti	Rural etc	9	33	27%
Western Heights (Rotorua)	Major Urban	9	34	26%
Waikanae	Secondary Urban	10	39	26%
Manukau	Major Urban	24	99	24%
Mangapapa (Gisborne)	Major Urban	9	39	23%
Ngakuru	Rural etc	9	40	23%
Christchurch	Major Urban	37	180	21%
Orewa	Major Urban	8[†]	40	20%
Parawai (Thames)	Minor Urban	9	47	19%
Rangatira (Taupo)	Secondary Urban	9	48	19%
Tamatea North (Napier)	Major Urban	9	49	18%
Waitakere	Major Urban	16	96	17%
North Shore	Major Urban	19	119	16%
Auckland	Major Urban	38	240	16%
Awhitu	Rural etc	9	59	15%
Overall		399	1687	24%

Table 14: Participation rate of households asked to participate in the HEEP study

Note: [†] The Orewa cluster was originally intended to be nine houses in size; however there was a late withdrawal by one of the households. The households contacted for this non-participating household have been excluded from the count.

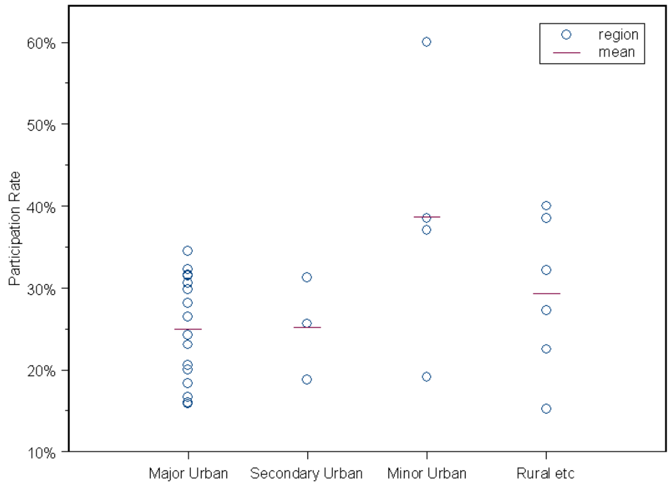

Figure 23: Regional participation rate by urban level

The small numbers of regions in each group make it difficult to make any inference on the mean participation rate for each urban level. Grouping the Major Urban and Secondary Urban together into an 'Urban' group and the Minor Urban and Rural areas together into a 'Small Town/Rural' group gives a significant (p 0.03) difference between the mean participation rate in for the Urban regions (25%) and the mean participation rate for the Small Town/Rural regions (33%).

There are likely to be many factors that influence whether a particular household participates in a survey. One of the HEEP regional data collection co-ordinators has noted that 'only nice people' decided to take part, and that they could commonly be grouped into a number of categories: those who wanted the gift; those interested in understanding their energy use (often 'why are my energy bills so high?'); and those who were community-minded and generally took part in surveys.

An important factor for recruiting households to participate in a study appears to be the quality (clarity, authority, completeness) of the material sent to them and the impression made by the contact person. With the HEEP selections involving a number of different contact people taking place throughout the country over a number of years, the importance of this factor is difficult to estimate. A particular example is the very high participation rate in the Wairoa cluster which could, in part, be due to many of the householders already knowing the Wairoa HEEP data collection co-ordinator.

During monitoring, 20 houses (5%) had a change of occupants. This compares to the 2001 Census which reported that half of the people in New Zealand on Census night 2001 (Statistics NZ, 2002a) had changed their usual address at least once since 1996 – about 10% movement a year, or twice that of HEEP. It is possible that people expecting to move decided not to take part in the HEEP monitoring, and thus self-selected themselves out of the sample.

4. MONITORING AND DATA

4.1 What HEEP measured

A wide variety of parameters were modelled and measured in each house, including energy use, temperature, appliance types, shower flows and hot water system characteristics, as summarised in Table 15.

	Count
Total load and hot water houses	293
End-use houses (EUM & SAM)	104
Energy Intellect remote reading meters	8
Hot water cylinders monitored	440
• Wet-backs	65
• Solar hot water heaters	5
Solid fuel burners	206
Solid fuel ranges	7
Open fires	42
LPG heaters	175
Diesel (fuel oil) heating	2
Spa pools	26
Heated swimming pools	2
Living room temperatures	774
Bedroom temperatures	380
External temperatures	37
Other room temperatures	30
Litres of each hot, warm and cold water (measure temperature and shower flow)	~1000
Photos of appliances, monitoring equipment and the houses	~8000

Table 15: What did HEEP record and measure?

Energy consumption was monitored for all fuel types (electricity, gas, solid fuel, LPG, solar).

74% of HEEP houses had total load monitoring, which was usually the total for each fuel type and the domestic hot water heater (DHW) heater, plus any solid fuel burners or LPG heaters.

In about one in four houses (26%), detailed end-use monitoring was carried out, which added monitoring of fixed lighting and cooking circuits, plus individual electrical appliances.

Details on each hot water cylinder were recorded, and depending on the fuel supply either each cylinder or the combination of all cylinders was monitored. The relatively small number of solar water heaters meant that it was not possible to provide detailed information on their contribution to hot water supply.

Information on space heating appliances was recorded, with solid fuel burners the most common large heating appliance. A small number of houses had oil-based heating, and slightly more had a solid fuel range which was often used for cooking and water heating. Spa and swimming pools were present in only 7% of houses.

Apart from the early houses in Wellington, at least two living room and one bedroom temperature were recorded. Table 15 also documents the number of external temperatures and temperatures measured in other rooms.

An appliance audit documented all electric appliances, including information on the make, model, location, power and standby power. Standby power measurements were made using an *Avometer M3050P* or an *ELV EM 600 Expert*[6] wattmeter.

35 mm film photographs were taken of major appliances and many smaller appliances, house exteriors and the placement of all sensors. This photographic record has proved invaluable in allocating ages to refrigeration appliances and matching measurements to monitored appliances.

Table 16 summarises data that is now held in an appliance database. In later years, data collection was rationalised with all appliances continuing to be listed, but full details were recorded only for selected appliance types, such as whiteware and entertainment.

Appliance database	**Counts**
Power measurements made	13,862
Appliances labels read	5,755
Photos of appliances	~2,400
Appliances in the database (excludes lights)	11,839
Appliances recorded in survey (includes lights, excludes washing machines, dryers etc)	17,264

Table 16: Appliance database

A physical audit was carried out of each house, which involved a detailed inspection, recording details of its location, construction, dimensions, heating systems and hot-water system (including shower water flow rates and temperatures).

An occupant survey was conducted by a specially trained member of the installation team. As soon as possible after installation, the survey responses were checked and loaded into a database.

Locally employed field staff visited each month to download the data and send it to BRANZ for processing and checking. Final processing was usually not completed until several months after monitoring finished.

Each house was monitored for at least 11 months (always including winter), with the following month set aside for equipment maintenance, calibration and the installation logistics.

4.2 Installation of monitoring equipment

Monitoring equipment installation was carried out by teams of three or more people plus an electrician, and a gas-fitter if required. It typically took two to four hours to instrument and survey each house and carry out the physical audit, appliance audit, and occupant survey, depending on its size, number of fuels and appliances and monitoring complexity.

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[6] A low cost wattmeter (approx. € 40, $US 50) - see www.elv.de

4.3 Removal of equipment

After monitoring was completed the equipment was removed. The download person normally co-ordinated this with the electrician and gas-fitter who were involved in the installation. A brief closing survey was carried out by the download officer to record any changes that happened over the year. The removal was fast, with 10 removals per day possible as the loggers were not downloaded until later. The data was then processed and final checks carried out, and a home report prepared using S-PLUS and given to the occupants.

4.4 Personnel and travel

Approximately 800 person days were spent installing monitoring equipment over about 40 weeks. The 2004 installation teams included students studying for the paper 'BBSC 331 Environmental Science' in the School of Architecture, Victoria University of Wellington, who used the experience to learn about issues of research and data collection in the field.

Table 17 tabulates the number of people involved in the research, including those based at BRANZ working either primarily on HEEP or involved in providing ongoing specialist support, download field staff, temporary installation people, and householders. Over 1,200 people were involved.

Role	**Number**
BRANZ Ltd HEEP team	9
Contract staff	5
Other BRANZ Ltd staff	5
Download field people	12
Electricians and gasfitters	26
Temporary installation people	47
Total number of people in HEEP team	**104**
House occupants (397 random houses)	1,143
Total number of people involved with HEEP	**1,247**

Table 17: HEEP people

Table 18 provides an estimate of the distances travelled by the field download staff, who covered over 126,000 km to collect the data.

Monitoring year	**Locations**	**Approximate distance (km)**
1999	Wellington	8,400
2000	Hamilton	5,500
2001	Auckland, Manukau, North Shore, Waitakere	17,500
2002	Auckland, Christchurch, Manukau, North Shore, Waikanae, Waitakere	22,670
2003-04	Arapuni, Dunedin, Invercargill, Kaikohe, Kamo West, Minden, Oamaru, Tauranga, Sherwood Rise, Foxton Beach	29,230
2004-05	Awhitu, Mangapapa, Ngakuru, Orewa, Rangatira Seddon, Tamatea Nth, Thames, Wai-iti, Wairoa Western Heights	43,060
	Total mileage for all areas and download staff	***126,360***

Table 18: Estimated distance travelled by HEEP download staff

4.5 Data collection equipment

A range of specialist monitoring equipment was either purchased or designed and built by BRANZ.

Two types of electric end-use monitoring systems were used:

- EUM (68 houses) – a purpose-built, commercial, power line carrier system, that allows monitoring of up to eight fixed electric circuits e.g. lighting, stove etc, and up to eight remote uses e.g. dishwasher, television, etc.
- Siemens Appliance Monitoring (SAM) (36 houses) – a standard Siemens revenue meter with a pulse output that feeds into a BRANZ Ltd data logger.

Both end-use monitoring systems provide high resolution data on appliance electricity use.

Early in the project it was found that commercially available data logging equipment with acceptable accuracy, resolution and storage capacity was either unavailable or too costly to permit the desired coverage to be achieved within a limited budget. A basic data logger design that had already been developed by BRANZ was modified so it could be used for temperatures, pulse counting and thermocouples to the specifications required. 750 BRANZ data loggers were built for use in the HEEP work, which proved to work extremely well. Now HEEP is completed, much of this equipment is being used on other projects.

Monitoring equipment	Number
BRANZ Ltd Temperature loggers†	313
Tiny Tag Internal Temperature loggers	65
Tiny Tag External Temperature loggers	15
BRANZ Ltd Pulse loggers†	245
BRANZ Ltd Microvolt loggers†	190
• Thermocouples†	~1500
Siemens Electricity Meters	275
EUM power line carrier electricity meters	12
• EUM Appliance Transponders	30
Siemens Appliance Meters (SAM)	30
Energy Intellect remote reading meters	3

Table 19: Monitoring equipment

† Designed and made at BRANZ Ltd

HEEP also made early use of the remote-reading electric 'smart metering' developed by Energy Intellect Ltd (formerly Total Metering Ltd – referred to as 'TML meters' in this report)[7]. From 2002, three sets of TML meters were placed on three houses for one year[8]. They replaced other HEEP metering, and provided both real and reactive power every minute. The data was provided directly to the HEEP team through a web-based interface.

Over the life of HEEP, a large number of 9 V and 3.6 V batteries were used to power the data loggers. The spent 150 kg (approximately) of batteries were recycled through Tredi New Zealand Ltd.

4.5.1 Logger calibrations

All HEEP monitoring equipment was subject to regular maintenance and calibration. All BRANZ temperature loggers were calibrated against a reference standard annually before they went out into the field. From September 1998 to July 2004, 1,021 loggers were calibrated. This was carried out in 49 batches, averaging 21 loggers per batch. Each calibration involved at least three temperature set-points (3,230 set-points in total).

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[7] Website: www.energyintellect.com

[8] One house-year of data was lost due to monitoring issues.

4.5.2 Equipment destroyed or damaged

During installation and monitoring, two cars and one van were damaged. One toolbox was driven over, seven laptops died in service (but not in vain …), a few loggers were melted or drowned, and one set of monitoring equipment was taken over by a cockroach infestation. Most installation equipment remained in use throughout the project, although a number of small whiteboards (used for house identification in photographs) have shifted to other parts of the universe.

Given the size and complexity of the monitoring work, remarkably few households were damaged or otherwise affected. In all cases, the HEEP team arranged for repairs to be made, and suitable compensation was paid for any damage:

- Five fridges/freezers were accidentally defrosted.
- Five other appliances were damaged sufficiently to require repair or replacement.
- One temperature logger fell from its wall mounted location and destroyed a porcelain ornament.
- In one early house, the monitoring of the wet-back hot water heater resulting in a water leak damaging the contents of a linen cupboard – after this, the flow rate monitoring of wet-back water heaters was discontinued.
- Two houses were damaged when removing meters.
- Two LPG cabinet heater incidents occurred – although neither appeared to be directly caused by monitoring equipment.
- One large bottle LPG connection valve was repaired.

4.6 Data processing

The HEEP time-series data consisted of multiple energy and temperature measurements, stored in a database in the statistical analysis program S-PLUS. A number of steps needed to be carried out before the raw data for each house was transformed into the S-PLUS format. It was important to ensure that the processing steps were completed as soon as possible so that any problems with the equipment setup could be corrected.

A rough schematic is shown below. An internal monitoring report has been prepared which holds details on all aspects of the data processing.

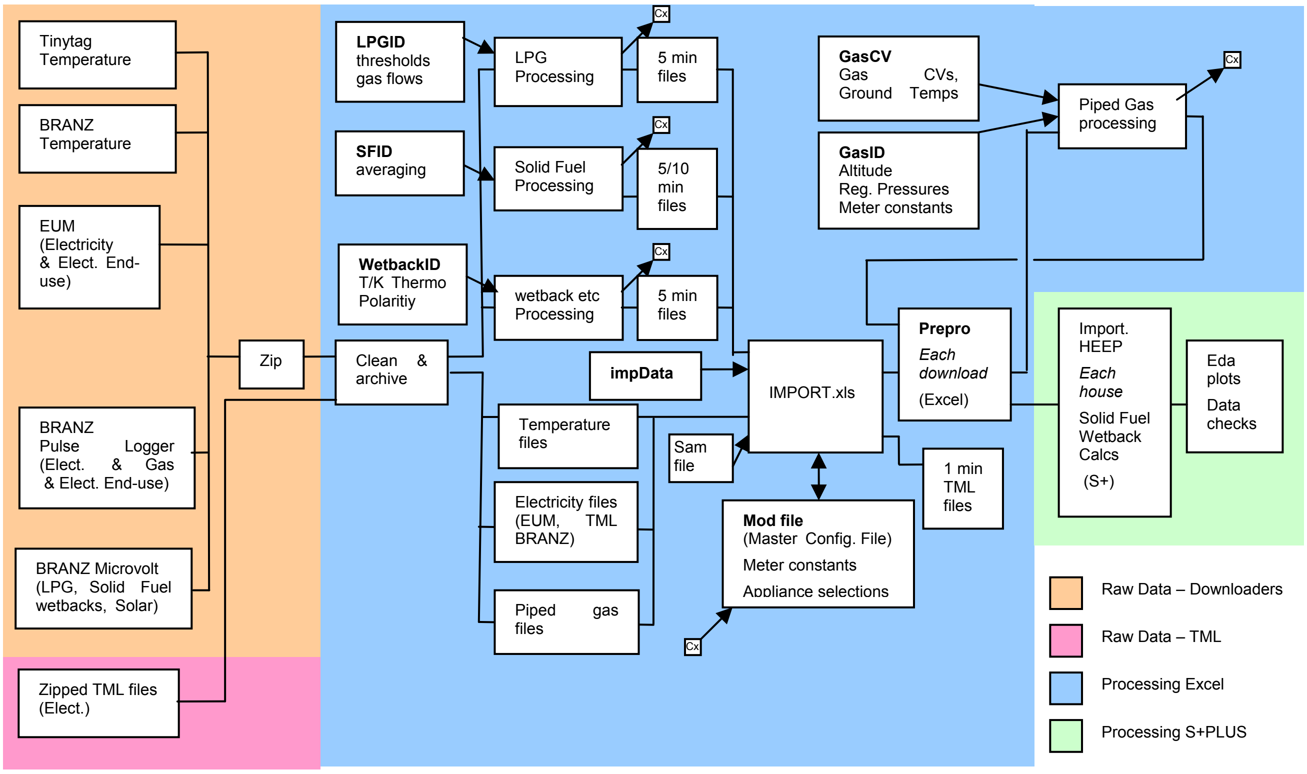

Figure 24: Schematic of HEEP data processing

Loggers were downloaded in the field, producing a series of raw data files which where then compressed (WinZip) and emailed to BRANZ. Data from the TML meters was collected by Energy Intellect on a daily basis, compressed and emailed to BRANZ once a month.

A separate raw data archive was maintained for each download region. This had individual directories for each logger file type so that multiple selections of logger file types could be made easily.

Files taken from a data loggers were 'cleaned' by converting them into a text format (comma separated variables) that could then be processed by specifically designed Excel VBA import routines. The different types of loggers required their own data cleaning processes, to handle the different file formats and types of errors.

All data for each download for each house was collated into a single file with a 10 minute timebase (known as a 'prepro' (pre-process) file). IMPORT.xls, an Excel program, created these files. An example of the prepro file can be seen in Figure 25. This was the first stage in the process that combined data for each house.

Date	Time	TempTfra	TempTfrb	TempTb1a	SubEttt	dhwEttt	rangeEttt	lightEttt
4-Nov-02	13:50	21.33	19.82	17.614	402	0	0	0
4-Nov-02	14:00	21.3	19.82	18	312	0	0	0
4-Nov-02	14:10	21.33	19.82	18	234	0	0	0
4-Nov-02	14:20	21.43	19.88	18	246	372	0	0
4-Nov-02	14:30	21.5	19.91	18.014	270	1626	0	0

Figure 25: A section of a prepro file

Any non-valid measurements (such as spikes at the start and ends of files) were removed in the prepro files, and the raw data files were never changed in any way. This ensured there was always an original file available.

Traceability of the changes made to the prepro was achieved by manually entering a description of the modifications into a summary spreadsheet called a ‘Modfile’. The Modfile also acted as a configuration file for constructing prepro files, listing the column headings. In conjunction with the pre-processing spreadsheet, the Modfile automatically inserted formulae into specified columns of the prepro file, a useful feature when constructing totals from separate measurements or when residual usage could be identified, for example subtracting gas water heating from gas total to calculate gas heating usage.

A number of processing routines also wrote information into the Modfile. These are discussed in section 4.7.

4.7 Specific fuel type processing

All logger datafiles needed specific processing even if they were measuring the same energy type. For example, electrical energy use was measured in a number of ways (listed in Table 20) but was consistently recorded as average power in the prepro files.

Measurement method	What it measures for interval
EUM	Average Power
Siemens Meter with a BRANZ pulse logger	Wh
Siemens Appliance Metering (SAM) with BPL	meter constant × Wh
TML	kWh

Table 20: Logger electrical energy measurement units

The IMPORT.xls program automatically handled the specific processing for electricity and temperature measurements.

Data collected by the Siemens Appliance Meters (SAMs) required special processing. These used Siemens meters modified to increase their sensitivity for monitoring plug-in appliances. Each SAM unit had a unique calibration coefficient that needed to be tracked, as the SAMs could be moved from download to download. The meter numbers for the SAMs boxes were recorded into the Modfile and IMPORT.xls picked up the meter calibration coefficients from the appropriate calibration file.

The integration of TML data into the IMPORT.xls program proved to be a sizable task as the format of this data differed considerably from other types. The TML data was remotely collected (via a cellular connection) on a daily basis at a logging interval of 1 minute, and the previous month’s files were zipped up and emailed. As HEEP downloading was generally some weeks into the month, rather than at the end of the month, there was a small delay in processing these files until the appropriate TML data had been sent.

The TML files were converted into a forward facing time series displaying average power (calculated from reported kWh). The order of the file was also converted to the standard first-in first-out (FIFO) format rather than the last-in first-out (LIFO) format used by the TML files. A series of daily files were then merged to cover the download period reported by the other loggers used in that household for that download. The data in these merged files was then output as an editable (tracking changes in the prepro file) Excel spreadsheet. These merged files were then aggregated to a 10 minute period and used to build up a prepro file for that download.

BRANZ pulse loggers were also used to record piped gas usage. The routine in the IMPORT.xls program took the raw 1 and 2 minute readings and aggregated them into a 10-minute series. A separate ‘gaspro.xls’ macro was run over the prepro file which applied a series of correction factors for daily gas calorific values (supplied daily by the Natural Gas Corporation), gas (i.e. ground) temperature, gas pressure and meter height above sea level. As there were manual stages in the preparation of these input files, it was generally left to after the final data had been downloaded before these correction factors were applied (although the unconverted data was checked at each download to identify any logging problems).

4.7.1 Microvolt loggers

The output of the microvolt loggers was the reference junction temperature along with the microvolt readings for each of the three thermocouples. The microvolt loggers were set to either 5 or 10-minute logging intervals. The LPG processing was based on 'on' or 'off' readings, so processed the raw microvolt readings rather than actual temperatures. The wetback and solid fuel routines processed the microvolt readings into temperatures. An intermediate data step, as for the TML processing, was used.

The intermediate file for the LPG heater processing calculated setting combinations for the heating based on thresholds stored in the LPGID configuration file at each separate time step in the file. The LPG processing routine then assigned an energy output for the assigned settings. The IMPORT.xls procedure then stored this value into the prepro file for that particular heater.

4.7.2 Merging into single house files

Once the data had been stored in the prepro files, it could then be imported into S-PLUS to create one file per house. The solid fuel and wetback/solar processing was undertaken in S-PLUS as part of this importing procedure, and some extra columns calculated.

Data was then graphed and checked, and EDA (Exploratory Data Analysis) plots like Figure 26 were printed for all houses. These summarised all the data into a profile with a rolling average which was a very useful format for spotting errors in data (such as temperature spikes from the sun hitting the logger), as well as giving the 10 minute data for all downloads. All the data were visually inspected after each download and after monitoring finished, and any anomalies checked and corrected if necessary.

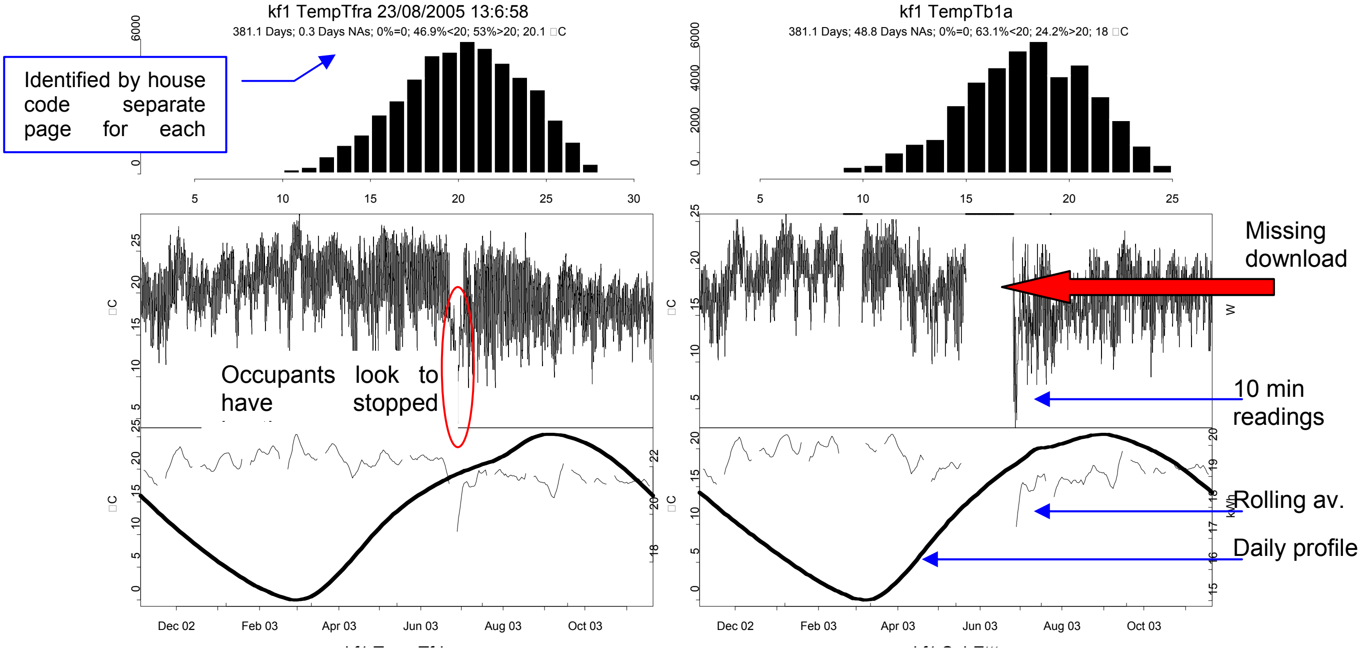

Figure 26: Sample EDA plots for two temperature sensors

4.8 Data reliability

This section quantifies how much data is missing from the HEEP database due to equipment failure, data problems and set up problems.

One method of determining how much data is missing involves calculating the date and time between when the house first had data, and when the data finished. This therefore includes data that is missing due to the electrician installing equipment late, or monitored data from equipment that was installed incorrectly and removed. Not all monitored data can be looked at in this way as some appliances were only monitored for one or a few downloads. For appliances, just because data is missing does not mean monitoring failed. Written records of the appliance monitoring were kept on the download sheets for each house, and problems with data were recorded on the modfile for the house.

This method covers room temperature, circuits monitored on the circuit or fuse board (total electricity, hot water electricity etc), natural gas and solar hot water heaters. It does not cover appliances, portable LPG heaters, solid fuel heaters and wetbacks. There is often more data missing for LPG and solid fuel as they used thermocouples that on occasion could get burnt out, especially if placed in the fire box. If the wires for the thermocouples crossed they shorted – this could happen due to the wire insulation being burnt, rough handling, or being installed incorrectly.

The range of missing data for circuit data houses is from 0.1% to 60.8%.The range, Median and Minimum for the individual circuits monitored are shown in Table 21.

Summary of missing data by circuits	Percent Missing (%)
Median	9.3
Mean	15.3
Minimum	0
Maximum	98
Count of circuits	2984

Table 21: Summary of missing data by circuit

Table 22 provides statistics on missing data by house.

Summary of missing data by house	Percent Missing (%)
Median	3.9
Mean	4.5
Minimum	0
Maximum	26
Count of houses	399

Table 22: Summary of missing data by House

Overall, the standards of equipment installation, data collection and processing improved with experience, as seen in Table 23.

Year Monitored	Data missing (%)	SD	Circuits monitored
1999	17	2	195
2000	7	1	169
2001	26	1	362
2002	15	1	696
2003	17	1	757
2004	11	1	804

Table 23: Missing data by year of monitoring

There was an increase in the percentage of missing data in 2001 and 2003. For 2001 there was a large increase in the number of houses monitored at the same time and multiple monitoring locations. 2003 was the first year of monitoring clusters, and required a lot more field workers. In both 2003 and 2004 there were a number of new download people and tradespeople.

Table 24 shows missing data by regional council.

Regional Council	Percent missing (%)	S.D. of percent missing	Number of circuits monitored
Northland	8	0.8	206
Tasman/Nelson/Marlborough	8.6	0.8	149
Taranaki/Manawatu-Wanganui	8.9	1.8	72
Gisborne/Hawkes Bay	12.7	1	199
Waikato	13	0.8	499
Canterbury	16.3	1.1	252
Wellington	16.5	1.3	272
Auckland	17.9	0.7	862
BOP	18.5	1.3	245
Otago/Southland	21.1	1.4	227

Table 24: Missing data - Regional Council

4.8.1 Different types of monitoring

There were two different types of meters used for monitoring electricity at a circuit level (Section 4.5). Table 25 shows the percentage of missing data for both EUMs and SAMs. EUMs have 4% less data missing than SAMs, but EUMs monitored less than half the number compared to SAMs.

	Percent missing	Number of circuits
SAM circuit monitoring	18	878
EUM circuit monitoring	14	352

Table 25: Missing data - SAMs versus circuit monitoring

Table 26 shows the two different loggers used for recording inside temperatures. Tinytag loggers have more missing data and they monitored less than half of what the BRANZ temperature loggers monitored.

	Percent missing	Number of circuits
BRANZ temperature logger	8	871
Tiny Tag temperature logger	12	312

Table 26: Missing data - Tinytag versus BRANZ temperature loggers

Table 27 shows that 20% of TML data was missing from the nine monitored houses. One of these went the whole monitoring period with an incorrect setup, resulting in total electricity not being recorded - this circuit has not been included in Table 27. This mistake occurred because data was not fully checked until after the removal of the equipment. These results again emphasise the importance of checking data as soon as possible after the monitoring period.

	Percent missing	Number of circuits
TML	20	72

Table 27: Missing data – TML

The numbers reported above do not include cases where the whole circuit was removed due to data issues (such as the total electricity circuit missing in the TML house). These were mostly in the first year of monitoring where methods were still being developed (Table 28). These houses were missing either the total electricity or the total gas. As the import program into S-PLUS was programmed not to import circuits which had no data, it was difficult to search for houses that may have had other circuits missing.

Region	Number of houses	Year of monitoring
Wellington	4	1999
Auckland	1	2001
Northland (TML house)	1	2003

Table 28: Circuits missing

4.8.2 Reasons for missing data

Table 29 provides a summary of the different reasons that data was lost from the different types of loggers.

Problem	Loggers that are affected			
	BRANZ temperature	Tinytag	Pulse	Microvolt
Battery goes flat and data is lost	✓	✓	✓	✓
Battery goes flat during downloads – part of the month is not monitored	Uncommon	Uncommon	✓	✓
Wires cross – short circuiting			✓	✓
Placed in sunlight, or beside a heating source	✓	✓	-	-
Wires are loose			✓	✓
Thermocouples burn out				✓
Thermocouples move				✓
Battery connector becomes loose	✓		✓	✓
Logger was not erased or failed to erase†	✓		✓	✓
Logger overwrites data*	Uncommon	Uncommon	✓	✓
Logger was not downloaded	✓	✓	✓	✓
Logger not put back to position for logging	✓	✓	✓	✓

Table 29: The most common reasons for missing data

†if battery is not connected to the logger in one movement, bouncing occurs and the microprocessor is rapidly stopped and started which will sometimes cause the microprocessor to go into a faulty mode where the previous data is not erased and no more is written.

* Possible for all types of loggers, but temperature loggers have a larger memory

A small number of loggers stopped working during the study for unknown reasons, but the numbers reduced as the loggers were improved.

4.9 Meteorological data

Meteorological data was collected by BRANZ at each location (city or cluster). External temperatures were collected from a screened temperature logger, and data was also taken from the NIWA CLIDB database. This data was stored as part of the S-PLUS database and used for analysis as needed.

4.10 Survey data

Information from the occupant survey, closing survey, and installation setup sheets (power measurements of appliances, shower flow rates) formed a set of 'static' data for each of the households examined. This data set included:

- household
- physical house
- people (occupants)
- DHW systems
- heaters
- monitored appliances
- cooking appliances
- surveyed appliance groups
- inspected appliances.

The survey data was initially entered and stored in Excel worksheets. However, this was inadequate for analysis and storage, so in 1998 the survey was transferred to an Access database.

4.10.1 CRESA's involvement

CRESA's involvement with the HEEP project began in June 2003 it was contracted to provide review and guidance on the collection of data, analysis, development of the HEEP model, and the communication of results. Prior to this, Gerard Fitzgerald of Fitzgerald Applied Sociology provided social science support.

CRESA's second task was to explore importing household survey data from the Access database into an SPSS database to allow more flexibility in data analysis. However, it was decided to re-enter all the data from the original survey forms to ensure a consistent data entry and checking process to CRESA's standards.

CRESA used a number of strategies to minimise data input error and maximise data integrity, including:

Use of a limited number of data entry staff: the data entry team was limited to three individuals, all of whom received detailed training regarding the structure of the database, tracking rules and the rationale for coding.

Pre-coding: a senior researcher went through all surveys and pre-coded questions. This reduced the need for people entering data to make substantive decisions while inputting. Pre-coding was particularly critical on the earlier surveys where the unique codes for missing and non-applicable data had not been used.

Quality control: As each batch of surveys was inputted a random sample of 10% was selected and printed out. One of the data input team then sat down with the print out and the original surveys and hand checked each field for errors. Once this was complete a preliminary set of frequencies was run for each batch. These were then checked by a senior researcher for obvious data input errors and internal tracking consistency.

Once all data had been re-keyed a reconciliation of the SPSS data with BRANZ records was undertaken to ensure all surveys were accounted for. This process revealed that there had been changes in a small number of households over the monitoring year. In some cases a change in household meant a new survey had been completed resulting in the total number of surveys being greater than the total number of dwellings. This was problematic for the social analysis in terms of determining a baseline denominator and for the wider analysis in terms of matching household characteristics and behaviours to the monitored data. A decision was made to limit the analysis of the social data for the model to the initial survey at each dwelling, any subsequent surveys were noted as 'duplicates' for that dwelling and excluded from the social analysis. This rule allowed the denominator to be stabilised for analysis purposes. The unit of analysis was taken to be the original household in any dwelling monitored. This denominator was 394 reflecting the 399 randomly selected households less the 2 households for which no measurements were recorded (c02, x49) and the households for which no survey was undertaken (c15, c32, kc4).

Where data collection will continue over multiple years, decisions around data input and storage should take into account as much as practicable the analysis the data will be used for. A balancing will be required between a database that allows easy input and one that allows maximum flexibility for analysis and data sharing.

4.10.2 Survey integration

In order for BRANZ to make use of the social survey information for analysis the SPSS database was imported into the S-PLUS system. The SPSS database was broken up into a number of entity tables (based on the original Access tables); however, there remains much redundancy in these tables due to the codes such as 'n/a - no more occupants in house' used in the SPSS datasets.

There is an amount of additional survey information that CRESA did not enter, such as DHW systems, shower flows and temperatures, and appliance power measurements and standby power. The material that CRESA entered in the SPSS was removed from the HEEP Access database structure so that the residual structure could be used to store the additional information. The house control table and some other data dictionaries were also kept. This additional survey information is accessible to S-PLUS using the original linkages between S-PLUS and ACCESS.

4.10.3 House data

A wide selection of information relating to each building and its operation gathered from the house audit and occupant survey was entered into the appropriate databases. Simulation programs (all houses were modelled in ALF3), however, require detailed information on such items as wall areas, degree of shading, etc., and this information was determined from examining the floor plans (and photographs) created at the time of installation. House plans are stored separately from other paperwork for easy reference.

An Excel macro was created that compiled all the results from ALF models into a single spreadsheet that could be imported in S-PLUS for analysis alongside other data. This macro was preset to produce a variety of outputs (heat loss through wall, floor, etc.) and could also summarise the input data as well (amount of north facing glazing, etc.). The spreadsheet could be set up to produce other ALF inputs and outputs by modifying the Excel macro.

5. SAMPLE STRUCTURE AND ESTIMATION METHODS

While a great deal of other information was obtained from the HEEP study, the over-riding design consideration was the ability to provide unbiased estimates of the power consumed in various end uses (e.g. heating, refrigeration, water heating), over New Zealand as a whole, and hopefully in various geographic strata, over the period of the survey. It was also highly desirable that the precision of these estimates should be measurable. In this section the sample design and statistical estimation methods used to ensure that accurate and reliable estimates were possible are discussed in detail.

5.1 General comments on bias

All surveys are subject to incalculable bias due to things like non-response, missing data and inaccurate measurement. Ad hoc adjustments are possible on the assumption that such defects occur effectively at random, but this assumption is unlikely to be true. In practice the only thing to be done is to try to keep such defects to a minimum, and hope that the resulting biases are not too large. Estimates of survey precision do not normally take into account this type of bias.

Surveys like HEEP, in which appliances of different types were selected for monitoring from an inventory that varied from house to house, are also open to another form of selection bias, as the more appliances a household has, the less likely it is that one particular appliance will be selected, which unless corrected for will lead to an over-representation of appliances from housesholds with few appliances. To avoid this involves considerable care in the method by which appliances are selected for monitoring and appropriate weighting of the results. A major feature of HEEP was the method used to avoid this bias.

5.2 Large scale sample structure

To select houses for HEEP, a stratified design was used, with strata consisting of the main centres of population and a ‘rest of New Zealand’ stratum, sampled as a cluster sample. Clusters were the area units defined for the NZ Census of Population and Dwellings, 1996. These were selected with probability proportional to the number of dwellings they contained, and a subsample of fixed size (nominally 10 dwellings) drawn from each. The remaining strata were sampled at random, using a sample size proportional to the number of dwellings in the stratum.

The sampling frame used was supplied by Statistics New Zealand from the 1996 Census. The number of dwellings in each meshblock was provided, randomly rounded to a multiple of three. To select a single dwelling within a stratum or cluster, a meshblock was selected with probability proportional to this randomly rounded size. The individual dwelling within this meshblock was determined by inspecting the meshblock, and selecting a dwelling within it using random numbers.

If this procedure is carried out accurately, then barring defects in the frame (which becomes more out of date as the survey proceeds) each dwelling in New Zealand has an equal probability of selection in the survey. This means that the survey is ‘self-weighting,’ that is that the simple average of a variable (e.g. total electricity consumption for each dwelling) over all dwellings in the sample gives an unbiased estimate of its average over the population of all New Zealand dwellings. The random rounding used in the sampling frame does not affect this property. The primary sampling units (variation among which determines the precision of such an estimate) are clusters in the ‘rest of New Zealand’ stratum and the individual dwellings in the remaining strata.

5.3 Effect of spreading the survey over time

If the survey had been carried out in a single year, with each house being monitored for the whole year, with estimates of precision available within each stratum, these could be combined to give an estimate of precision for the whole population for the year. However, the downside of this approach is that the year may not have been 'average,' and no estimate for the precision of the estimate for the given year as an estimate of the average year would be available.

By spreading the survey over a number of years, the estimates are given a chance to average out over time, and should thus be more representative of the true medium term average. However, the precision of the resulting estimate as an estimate of the medium term average cannot be calculated, because there is no way of distinguishing variation between strata (which does not affect the precision of the estimate) from variation between years (which does). If it were not for the stratum with cluster sampling, stratification could be ignored to proved an underestimate of precision (i.e. an overestimate of the standard error) and allowed for to provide an overestimate, with the true precision falling somewhere between. But the cluster sample requires an essentially different method of estimating precision from the rest of the survey. The method used was to estimate the precision of estimates as if all houses had been monitored over the same year, with the recognition that this does not allow for year to year variation, but that the results will give a more reliable indication of the medium term average than a single year would.

A source of bias may have arisen because of the need to spread the survey over a number of years, as the strata tended to get surveyed in order of difficulty, with major urban areas getting surveyed first, and the 'rest of New Zealand' cluster sample being done at the end. Some changes in consumption patterns took place over the time of the survey, and these may have interacted with the order of surveying. For instance, it is clear that the use of computers grew considerably over the period of the survey, and it is possible that it grew considerably more, or less, in major urban areas than in 'the rest of New Zealand.' If so, the interpretation of the energy used by home computers as an approximate average over the period of the survey may be questionable.

5.4 General principles of estimation

The 'rest of NZ' stratum was sampled using a cluster sample with probability of selection proportional to cluster size. Given an unbiased estimate of the mean power consumption per house within each cluster for any given end use, the stratum average can be estimated as a simple mean of cluster means, making no adjustment to allow for the different cluster sizes (this has already been done by varying the probability of selection.) The precision can be estimated from the sample of estimated cluster means, treating each mean as a single observation, and applying the 'sigma over root n' formula, where n is the number of clusters. Although the number of clusters is only one tenth of the number of houses sampled, the estimates of cluster means should be considerably less variable than the estimates for individual houses.

Within the other strata, the stratum average can be computed as the arithmetic mean of the estimates obtained for each individual house, and the standard error can be estimated using the 'sigma over root n' formula.

These methods were used initially to provide estimates for the Wellington stratum, but were later replaced by different methods as described in Section 5.8, as they proved very unwieldy in practice, due to the difficulties of imputing totals for individual houses in the presence of

Given estimates with estimated standard errors for each stratum, a combined estimate covering all strata can then be worked out as a weighted average of stratum estimates. The standard error of this combined estimate can also be estimated from the estimated standard errors of the stratum estimates, using a standard formula.

The estimates obtained for individual houses or clusters may be subject to large random measurement errors, particularly for variables wholly or partly monitored by the random placement of transponders (see Section 5.6). This does not affect the validity of the estimates of standard error, and the precision of the estimates for individual houses need not be estimated separately. This is in accordance with the general result given in Appendix 1.

5.5 Monitoring within houses

Some appliances within a house are connected to their own individual circuits. These were monitored at circuit level continuously throughout the year, by placing an appropriate device on the fuse board. Ranges, hobs and hot water systems are invariably wired in this way, and thus continuous records are available for these appliances. Similarly, all gas appliances, wood burners and LPG heaters were monitored separately. The degree of time resolution available varied considerably according to the fuel concerned. For electrical and gas appliances, the energy consumption was measured at ten minute intervals. For solid fuel burners, estimates at ten minute intervals were made by a combination of interpolation and modeling, incorporating temperature measurements and models of heat transfer.

Other appliances are operated by plugging them into power points, and for these appliances transponders were used. The transponders were attached to an appliance, not a power point.

All houses in the survey were monitored at the circuit level for certain key variables, including totals for each fuel type, hot water systems and central heating systems. Within each stratum and cluster, 25% of houses were monitored for end use. These are known as EUM houses, and in them additional appliances were monitored at circuit level, such as ranges and fixed wired electric heaters. Additional appliances were selected for monitoring at various times by transponder, as described in Section 5.6. Because of the fixed sampling fraction used, the EUM houses themselves form a self weighting sample.

Due to limits on the number of transponders available (2-3 per household), appliances to be monitored had to be sampled. Some appliances do not vary much in power consumption over a year, and it seemed a waste to keep a transponder plugged to such an appliance for the whole year. Thus, the transponders were moved around from appliance to appliance over the year, in a way described in Section 5.6.

Appliances which were not plugged into power points, but shared a circuit with other appliances, caused a problem. A common example is a bathroom heater sharing a circuit with an electric towel rail. In such cases there are several possible solutions. The appliance combination may be considered as a single appliance, and no attempt made to provide separate estimates for the components. For example, all bathroom heaters may be excluded from the space heating category, and included in their own 'bathroom heating' category, in which any towel rails are also included. Alternatively, the appliances may be rewired to enable them to be monitored separately, either using circuit level monitoring or transponders. A third possibility is to attempt, by scrutiny of the power consumption record concerned, to separate out the separate contributions of the heater and the towel rail. Another possibility is to abandon attempts to monitor combined heaters and towel rails, but to estimate the energy consumption of these appliances from dwellings in which separate estimates are available. In the case of heated towel rails, none of these methods were used, and a rough estimate of energy consumption was derived from the occupant self-reported survey of appliance usage.

For each house selected for monitoring, a list was made containing all appliances in the household, with those to be monitored by transponder identified.

5.6 Sampling of appliances for transponder monitoring

In sampling appliances within a house for transponder monitoring, it was critically important to use a well defined randomisation procedure such that the probability of selection for each appliance could be calculated. These probabilities did not need to be equal, but must all have exceeded zero: each appliance must have at least some chance of being selected.

For each house, a list was made up containing all appliances, with those to be monitored by transponder identified. Weights were assigned to each appliance, according to the relative desirability of monitoring it. This depended on estimated power consumption, variability over time and variability between houses.

The year was divided into several monitoring periods, of length approximately one month. At the start of each period, appliances to be monitored by transponder were selected at random. This was done by selecting one appliance with probability proportional to weight. A second appliance was then selected in the same way, repeating the draw until it came out different from the first appliance. If three transponders had been allocated to the house, the appliances for the third transponder was then selected, repeating the selection until it came out different from both of the first two. From the weights, the probability that each appliance would be monitored at any given time could be calculated, basically by enumeration of possibilities. The total over appliances of these probabilities was equal to the number of transponders allocated to the house. The probabilities in general varied with time, partly because of changes in the population of appliances to be sampled, as new appliances were bought and old ones discarded, partly because in some strata the weight used for electric heaters varied with time.

This procedure was implemented using a computer spreadsheet on which the appliance inventory was listed in various categories. Macros were used to assign weights to the various appliances, to perform the actual selection and to record sufficient information for the inventory and weights used to be reconstructed. Part way through the survey, a bug was found in one of the macros, resulting in an unintentionally high probability of selection for microwaves where there were no space heating appliances on the inventory. Fortunately the true probabilities of selection in the presence of this bug could be calculated, and used instead of the intended ones, via a simple correction. In fact, the number of houses where the bug had a chance to influence matters was fairly small. The bug was fixed when discovered.

5.6.1 Calculation of probabilities of selection

Computation of unbiased estimates in any particular end use involves calculation of the actual probabilities of selection at any time for each appliance in the inventory. If only one transponder is to be located, the probability of selection of appliance *i* is proportional to the weight assigned to that appliance. Call this the 'initial probability', denoted by p_i. If two transponders are to located, the probability that appliance *i* will be selected in one of the two draws is given by

$$f_i = p_i + p_i \sum_{j \neq i} \frac{p_j}{1 - p_j}$$

Equation 1

where the p_i are the initial, and the f_i the final, probabilities of selection. The formulae rapidly increase in complexity as the number of transponders increases, having essentially to take account of every possible sequence of selections in prior draws, and little possibility of algebraic simplification seems to exist. Fortunately no more than three transponders were ever placed in the same dwelling, and the computations for three transponders are manageable. The complexity of the calculations involved at this stage should be borne in mind in any survey in which substantial numbers of transponders per house are used. The sum of the final probabilities should add to the number of transponders, and this may be a useful check of programming logic.

5.7 Estimation within houses

5.7.1 End uses always monitored at circuit level (e.g. ranges)

This is straightforward as there is no sub-sampling involved. The contribution of each house to the total is known, and the appropriate methods for simple random or cluster sampling used to estimate the average per house and its standard error within each stratum.

5.7.2 End uses always monitored by transponders (e.g. vacuum cleaners)

Consider a particular appliance *i* at a particular time *t*. The probability that it is being monitored can be calculated: call it *p(i,t).* Let *P(i,t)* be its power consumption at time t (whether or not it is monitored). Let *P*(i,t)* be equal to zero if *i* is not monitored at *t*, and equal to *P(i,t)/p(i,t)* if it is.
Then P*(i,t) is an unbiased estimator of P(i,t), for:

$$\mathrm{E}(P^*(i,t)) = (1 - p(i,t)) \times 0 + p(i,t) \times \frac{P(i,t)}{p(i,t)} = P(i,t)$$

Equation 2

While unbiased, this estimator will have a large standard error, but summed over an adequate number of times and appliances can provide a reasonable estimate. For example, consider an appliance with a continuous power consumption of 10 W. If the monitoring probability is 0.05, we will estimate a consumption of zero 95% of the time and of 200 W 5% of the time. Over a long enough time, the average power consumption will be estimated correctly.

For a particular end use G, and time interval T, $P^* = \frac{1}{n} \sum_{t \in T} \sum_{i \in G} P^*(i,t)$ thus gives an unbiased estimate of the average energy consumption per house for that end use and time interval. The standard error of this estimate can be considerably reduced by ratio estimation. To this end a random variable Q(i,t) is defined, with values zero if appliance i is being monitored at time t, and 1/p(i,t) if it is not. Q(i,t) has expectation 1 for all i and t. When Q(i,t) is accumulated and scaled (to give Q) in the same way as the P*(i,t), the expectation of Q is equal to the expected number of appliance.seconds of monitoring per house. It the observed value of Q is higher than this expectation, it means that the appliances in G have been monitored more than expected, and P* may be expected to give an overestimate. This may be corrected using a ratio estimator

$$R = E(Q) \times \frac{p^*}{Q}$$

Equation 3

As discussed above, the standard errors of P* and Q may be estimated from the observed variation of the contributions of the various houses to the totals involved. Their covariance may be similarly estimated and thus a large sample estimate of the standard error of the ratio estimate obtained. In practice, as the number of houses monitored for end use in each stratum was modest, the ratio estimate was jackknifed[9], both to remove bias (which could accumulate over strata) and to give the estimate of standard error.

In Appendix 2 the theoretical large sample variance of R is calculated for the particular case that the probabilities of selection p(i,t) are constant, with exactly one relevant appliance in each house. The efficiency of the estimate is compared with the alternative of devoting the same monitoring effort to a smaller set of appliances, but monitoring them continuously. The results show that the alternative is always slightly more efficient at estimating power consumption at a given point in time (where only a single monitoring period is involved for each house), but that as the number of monitoring periods involved increases, the ratio estimate discussed above will eventually become the more efficient. The point at which the changeover occurs depends on the relative sizes of the within- and between-house variances, with high relative within-house variances favouring the alternative.

5.7.3 End-uses monitored by both circuit level and transponders

End-uses that have been monitored using both circuit level and transponder monitoring (e.g. space heating or cooking) could be dealt with simply by assigning to each circuit level appliance a selection probability p(i,t) of 1 and using the method for transponders. However, since circuit level appliances may well have different typical power consumption levels from transponder level ones (e.g. compare ranges and toasters) it is thought advisable to keep the two groups of appliances separate. Thus separate estimates are formed for each group, as discussed above, and these estimates added. To estimate the standard error of the combined estimate, it is jack-knifed over houses: that is, each house in turn is left out of both estimates simultaneously.

5.8 Application of the method in practice

While the computations outlined above are reasonably straightforward, in practice considerable difficulties were encountered due to missing data. The missing data took several forms, and we discuss these in turn.

5.8.1 Houses coming into and dropping out from the sample

The fact that the initial entry of houses into the survey was staggered meant missing data at the beginning. A calendar year was defined so that this effect (and the staggered dropping out at the end) were minimised. This probably did not cause a bias, as the order of coming in and going out can be reasonably assumed to be independent of house characteristics. More serious are houses that dropped out part way through. If this was because of unwillingness of the householders to continue to participate, there was little that could be done about it other than replace the house with some other drawn at random. This replacement did not remove bias, but at least kept the sample size up. In cases where a dwelling changed occupancy, every effort was made to continue monitoring under the new occupants, as if this

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[9] Jackknifing is a statistical computational technique which can be used to estimate the standard deviation by resampling the original data.

is done no bias will result. However, the information enabling the dwelling to be treated as a single unit must be available. The change in appliance stock can be catered for in the analysis methods.

Also more serious was the fact that in several strata the monitoring period was shorter than a full calendar year. This was to enable transponders to be moved from one stratum to another so that monitoring could commence in each stratum on approximately the same date, avoiding problems with school holidays and so on. This policy resulted in systematic absence of data for certain times of year, and was later abandoned. The imputation and estimation methods used were such that the biasing effect of this absence of data must have been substantially reduced, but it is better not to have the potential for bias there in the first place.

5.8.2 Problems associated with inadequately maintained sampling frames for transponder monitoring

Along with a mechanism to select appliances for monitoring, the selection spreadsheet had the important purpose of keeping a frequently updated record of the appliance inventory within each house during the period of the survey. This was perhaps not stressed as much as its importance warranted, and at least in the earliest strata to be surveyed the updating did not seem to be carried out systematically. Thus in some cases, appliances appeared on the spreadsheet which, when selected for monitoring, turned out to be no longer present in the house. In other cases, an appliance turned out to be present, but no longer used, so that it appeared to both to the monitoring staff and the occupants of the house to be a waste of time and money to monitor it. The correct treatment in such situations is to give a continuous record of zeros for the selected appliance. It is no use simply correcting the appliance inventory to remove the selected non-existent or unused appliance and then selecting another one instead. This would lead to consistent overestimation.

5.8.2.1 Example

To see this, consider an extreme case when half the appliances of a certain type listed on the inventories are non-existent or not used. Say 10% of these non-existent appliances are selected for monitoring, and their non-existence detected. In the other 90% of cases the non-existence is not detected. On average the percentage of appliances on the inventory that are non-existent would then be reduced from 50% to 45%. To this inventory an average power consumption **based only on appliances that exist** will be applied, resulting in overestimation by an average factor of 1/(1-0.45) which is approximately 2. To avoid this the average power consumption must be based on all appliances on the inventory, **whether they exist or not**. (A non-existent appliance, of course, uses no energy.)

This problem arose quite often, and was not easy to distinguish from the case where a selected appliance did exist and was used, but turned out to be impossible to monitor. In the latter case, it is more appropriate to treat the data as missing. Consequently, a significant part of the analyst's time had to be devoted to reconciling the appliances that were monitored with those that were supposed to be monitored, clarifying the situation where an expected record was missing, and in appropriate cases introducing an imputed record, either of zeros or of missing values, as appropriate. The substitute appliance, if any, then had to be discarded for the purpose of overall estimation: if appliances are going to be monitored by virtue of some other appliance being non-existent, unused or inaccessible, the probabilities of selection, which are required for unbiased estimation of the population total, are incalculable.

It may be important to note that this difficulty is not due to the use of varying probabilities of selection for the different appliances. A simple random sample of appliances from the inventory also leads to overestimation of the same type where appliances that turn out to be non-existent are replaced by other appliances.

Less frequently, cases were observed where appliances that did not appear on the inventory at all were monitored. It is not clear how this could have happened, except through the occupants switching transponders from one appliance to the other. In fact, cases occurred in which a transponder was placed on one appliance and subsequently discovered on another. In any event, if an appliance does not appear on the spreadsheet, no estimate can be made of its probability of selection, and therefore these data were unusable and had to be deleted.

Similar problems were encountered with changing inventories of fixed wired appliances.

Future surveys should anticipate these difficulties by consistently updating the relevant inventories and automatically providing material in readily usable form to the analyst to explain apparent inconsistencies between the appliances selected and the appliances monitored.

5.8.3 Problems associated with absent or incomplete data records for fixed wired appliances

For each fixed wired item on the inventory, the initial assumption is that it was present during the whole time of the survey – in this case a complete record of power consumption should be available. Short gaps due to downloads or malfunctioning of monitoring data were filled with imputed data. In other cases the following screening process was followed:

a) Were the data missing because the appliance did not exist at the relevant time? In this case zeros were inserted (after imputation, to avoid them being used in imputing other missing data) in the data record and the inventory record adjusted accordingly.
b) Were the data missing because the appliance was not expected to be used during the relevant period (e.g. outdoor swimming pools in winter?) In this case zeros were inserted in the data record without altering the inventory.
c) Were the data missing because the appliance was never used (for example appliances that no longer worked and had been superseded by others?). In this case the appliance was deleted from the inventory.

In other cases an attempt was made to impute the missing data.

After resolving as many situations as possible using the considerations described above, there remained a considerable amount of missing data. There were two stategies for dealing with this:

1) Over short time frames missing data was imputed as averages of non-missing data relating to the same time of the day and week within the same calendar month (circuit level monitoring) or monitoring period (transponder monitoring). This approach will fail if there is no appropriate data from which to compute the averages. This implies less than a week's continuous monitoring during the period, and in such cases results for the whole period were considered missing. It was not considered sensible to allow a monitoring period or month to be represented by data that did not cover the full week.
2) The sequencing of averages and totals involved in the estimation is largely irrelevant in the absence of missing data. However, where data is missing the order becomes important. In forming an average, it is important to consider by what average the missing data are effectively being replaced. Considerable attention was paid to this in deciding the details of the estimation method. In particular the estimation was broken into calendar months which were averaged last, to avoid as far as possible replacing data missing during a calendar month by a yearly average. If this precaution is not taken there is potential for significant biases arising for very seasonal appliances like heaters and swimming pools. Ideally it would be possible to use different ordering of

the estimation process for different appliances, to take account of their particular characteristics, but the amount of work involved in this ideal approach was considered prohibitive. The course of the analysis actually adopted is described in the next section.

5.9 The estimation technique in practice

5.9.1 Estimation for transponder-monitored end-uses

The data for the survey were given as a set of power readings for at ten minute intervals. These times at which the readings were taken will be called 'ticks.' For each appliance at each tick, a weight was assigned equal to the reciprocal of the probability that the given appliance was being monitored at that tick. For the set of appliances in a particular end-use group, the sum of the weighted powers for those appliances being monitored at any given tick is an unbiased estimate of the power being consumed by that whole set of appliances, monitored or not, at that tick. This property of unbiasedness is preserved when these estimates are accumulated over time, or over a group of houses. However, the properties of the estimate are considerably improved if, as well as the weighted power total; the corresponding sum of the weights themselves is also obtained, and used as the denominator in a ratio estimate. The sum of the weights is actually an unbiased estimate of the number of (unweighted) appliance-ticks within the end-use, group of houses and time interval being considered. This number is known, given accurate inventories in each house, and the power estimates may be adjusted accordingly, using the usual ratio estimate. The sum of the weighted powers is divided by the sum of the weights, giving an average power per appliance-tick, and this is multiplied by the known number of appliance ticks to give a total power. This procedure compensates for random under- or over-sampling of the end-use. It has also the practical advantage of yielding a reasonable estimate in the presence of missing data: if an appliance was selected for monitoring and the relevant transponder did not work for some or all of the relevant time, both numerator and denominator of the ratio are reduced and the overall estimate of power per appliance tick is still valid: it can still be multiplied up to give an estimate of total power.

The estimate of total power needs to be converted to a Watts/house basis, and thus the number of house-ticks to which the data relates needs to be calculated. A house was considered 'present in the survey' at a tick if after imputation data existed for any appliance in the house at that tick. (The inclusion of imputed data in the criterion allows for cases in which data was unavailable for moderate periods, for example, downloads.) The appliances in a house 'not present in the survey' were removed from the inventory for the relevant ticks.

5.9.1.1 Initial estimates in unclustered strata

For any end-use, denote by

P: the sum of the weighted power in a stratum
W: the sum of the weights in the stratum
A: the total appliance-ticks in the stratum
H: the total house ticks is a stratum

An initial estimate of the average power per house in the stratum is then obtained by

$$\frac{P}{W} \times \frac{A}{H} \times c$$

Equation 4

where c is a conversion factor to convert the estimate to Watts
This may be considered as applying an average power per appliance-tick to the average appliance-ticks per house.

5.9.1.2 Initial estimates in the clustered stratum

For the clustered stratum, it was necessary to give each cluster equal weight, although the numbers of house-ticks in the different clusters varied somewhat. This was required by the top level design of the survey, in which the clusters were selected with probability proportional to size. The aggregation was accordingly done in two stages. Subtotals were formed for each cluster. Each subtotal was then converted to a per-house tick basis, dividing by the subtotal corresponding to H. These divided subtotals were then aggregated over clusters to give P, W, A and H for use in the above formula. (H was then, of course, automatically equal to the number of clusters.)

5.9.1.3 Aggregation of monthly estimates over time

Separate estimates of this type were made for each calendar month of the year. This was partly because the monthly estimates would be of use in their own right, but mainly to avoid what would essentially be the use of an annual average to impute data missing in a particular month. This is undesirable in that some end-uses are highly seasonal. The separate estimates (weighted by the number of days in each month) were then combined to give an annual average.

5.9.1.4 Final estimates and standard errors: the Jack-knife

These initial estimates were then jack-knifed. Jack-knifing is a technique to provide a first order bias correction and an estimate of standard error for statistical estimates from a sample of *n* independent and identically distributed observations (possibly multi-variate). Essentially the estimate S is recomputed using all but one of the observations, leaving out each in turn to give a series of estimates S_i. ‘Pseudovalues’ $P_i = nS - (n-1)S_i$ are then calculated. The bias corrected estimate is then the average of the pseudovalues, and its standard error may be estimated by dividing the standard deviation of the pseudovalues by $\sqrt{n}$.

In the context of this survey the ‘observations’ left out were the totals for each house in turn in the unclustered strata and the totals for each cluster in the clustered stratum. Although the assumption of independent and identically distributed observations may at first sight seem rather inappropriate, it is in fact justifiable by virtue of the random sampling used. There is in each stratum a population of houses, (or, in the clustered stratum, clusters) any one of which could have been subjected to the sampling procedures used (and the accidents experienced) to yield a set of totals. The totals for the houses or clusters sampled are essentially independent draws of sets of totals from this single population. It is inappropriate to drop single houses in the clustered stratum because in this stratum the house totals cannot be considered independent because of intra-class correlations.

The bias correction feature of the jack-knife was desirable because ratio estimates are slightly biased, and the estimates had yet to be aggregated over strata. The standard errors would have been difficult to obtain by other methods.

5.9.1.5 Combination of estimates from different strata

Finally the estimates for the various strata combined into national and sub-national estimates in the usual way, weighting the estimates per house by the number of dwellings in the stratum.

For circuit monitored appliances, essentially the same procedure was adopted, with all weights being taken as 1. The imputation procedures for the two classes of appliances, however, differed somewhat.

5.9.2 Estimation for circuit monitored end-uses

For some circuit level appliances (e.g. woodburners) raw data was not available at ten minute intervals; however, the team managed to cast the data into this form using techniques based on interpolation and modelling. Since the primary output of the analysis being discussed is monthly and annual averages, the distribution of energy into ten minute intervals is not critical, but was necessary to avoid rewriting (and debugging) huge amounts of computer code, as well as for purposes outside the scope of the basic estimation technique being discussed.

5.9.3 Discussion

The method described here may seem very different and considerably more complicated than the method already described and justified mathematically. However, in an ideal survey, for which all houses are monitored all the time in accordance with the design and there is no missing data, the two methods are in fact equivalent and would yield the same answers. The more complicated route is necessary because of the imperfections of the actual, as opposed to the ideal, survey, where houses and appliances dropped in and out; transponders failed to work or were attached to the wrong appliance and so on. This route was such that adjustments were automatically made to allow for these imperfections, hopefully without introducing too much bias into the end result.

5.9.4 Special techniques for more difficult situations

5.9.4.1 End uses that are totals of separately estimated contributions

Some end-uses, for example domestic hot water, are the sums of components that are also separately estimated. The domestic hot water total has contributions from electricity, gas, solid fuel and LPG, each of which is separately estimated. If the contributions are totalled in each house, and the house totals then used to estimate the end-use total there are two problems:

a) The amount of missing data is increased, as missing data for any one of the components will result in missing data for the total.
b) Partly because of this, but also because of the technique of ratio estimation used, the estimate of the end-use total is in general not the sum of the estimates of its parts. This would be seen (although not necessarily correctly) to affect the credibility of the survey results.

Accordingly, such totals were normally estimated by totalling the overall estimates from the component parts.

The components could be estimated separately, and the estimates totalled, before the jack-knife was applied. In practice it was easier to compute and save the pseudo-values for each component, and accumulate these as necessary to give the pseudo-values for the required totals.

The exceptions to this policy were the totals for each fuel type. These were always monitored independently of their component parts and failure to match the total of these parts has to be attributed to failure to completely monitor all appliances or imprecision in their estimation.

5.9.4.2 End-uses consisting of two components, one estimated over all houses, the other estimated over end-used-monitored houses only

For example, gas central heating, LPG heaters, wood burners and most electrical central heating were monitored in all houses, but only in end-use houses were portable electric heaters and small fixed wired electric heaters monitored.

These situations were rather difficult to deal with. The estimates themselves were relatively simple to make: the averages per house of both relevant components were simply added. Calculation of the standard errors of these estimates was messy because of correlation between two contributions from end-use houses. Estimates of the correlation of the estimates for end-use houses were obtained by jack-knifing both the separate components and their total within the end-use houses, giving standard errors s_1 and s_2 for the separate components and s_{1+2} for the total. The covariance was then worked out as $g_{12} = (s_{1+2}^2 - s_1^2 - s_2^2)/2$. Now suppose that component 2 is estimated over n_2 end-use houses and component 1 is estimated over n_1 houses (including the end-use houses). Let the standard error of the jack-knifed estimate of component 1, estimated over n_1 houses, be S_1. Then the standard error of the total can be estimated as $S_{1+2} = \sqrt{S_1^2 + s_2^2 + \frac{2n_2}{n_1} g_{12}}$.

6. HEERA MODEL DEVELOPMENT

The development of a residential database and scenario model to store HEEP project information and to enable the stakeholders to utilise it to their best advantage is an essential part of the project and the subject of this report. This residential scenario model is referred to as the Household Energy Efficiency Resource Assessment (HEERA) model and database.

The HEERA model and database can be summarised as a modelling framework with which it is possible to:

- construct a set of energy use scenarios for the residential sector of New Zealand
- analyse and compare the energy use of these scenarios
- develop energy-efficiency actions and estimate the impact of the actions on scenarios.

The background and theoretical basis of the HEERA model and database, and the development of an Excel version of the HEERA model, were described in the HEEP Year 8 (Isaacs et al. 2004) and Year 9 reports (Isaacs et al. 2005). This section addresses the following aspects:

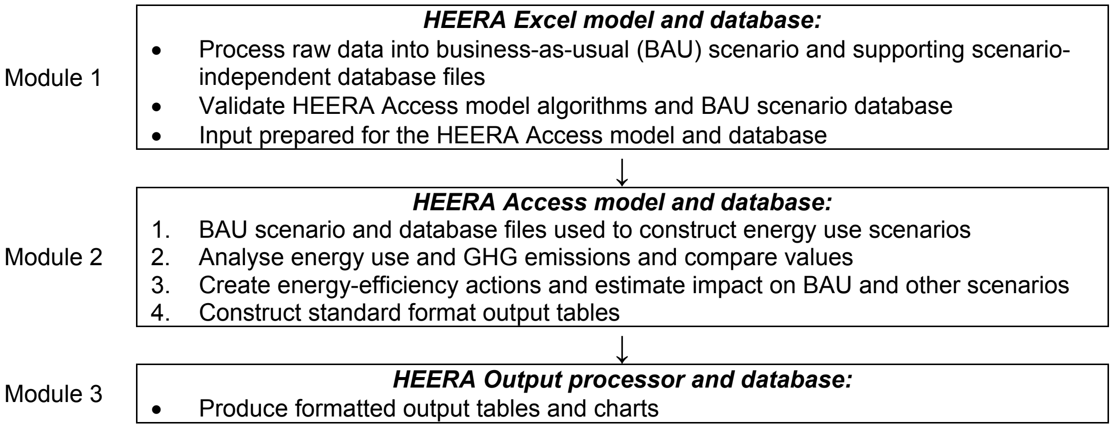
- development of the basic HEERA Access model structure
- demonstration of the use of the HEERA model to construct four scenarios.

6.1 Overview

The relationships, variables and drivers that determine the stocks and energy demand of the energy-using appliances used in the HEERA model have been discussed in the HEEP Year 8 report (Isaacs et al. 2004). These relationships, variables and drivers have been incorporated in dwelling and appliance stock algorithms, and in the energy use algorithms for the different residential end-uses. The algorithms are employed in the HEERA Access model and database.

The HEERA modelling structure is divided into three modules as shown in Figure 27:

- **Module 1: HEERA Excel model and database:** in this module raw data is processed with Excel spreadsheets into HEERA Excel business-as-usual (BAU) scenario-dependent and scenario-independent tables. These tables serve as input to the HEERA Access database. The HEERA Excel model validates the HEERA Access model algorithms and BAU scenario database tables, and checks that the data led to the correct values if the algorithms are applied to it.
- **Module 2: HEERA Access model and database**: this is the main module which provides the following capabilities:
  - constructs energy use scenarios for the residential sector of New Zealand
  - analyses and compares the energy use, energy supply and GHG emissions of the constructed scenarios
  - constructs energy-efficiency actions and estimates the impact of these actions on the BAU and other scenarios
  - constructs standard format output tables that contain the results of scenario analyses and comparisons, and the impact of energy-efficiency actions.
- **Module 3: HEERA Output processor and database**: the module uses the HEERA Access database standard format output tables to produce formatted output tables and charts according to the requirements of a HEERA user. This module could be in terms of Access or any other suitable modelling framework.



Module 1

HEERA Excel model and database:

- Process raw data into business-as-usual (BAU) scenario and supporting scenario-independent database files
- Validate HEERA Access model algorithms and BAU scenario database
- Input prepared for the HEERA Access model and database

Module 2

HEERA Access model and database:

1. BAU scenario and database files used to construct energy use scenarios
2. Analyse energy use and GHG emissions and compare values
3. Create energy-efficiency actions and estimate impact on BAU and other scenarios
4. Construct standard format output tables

Module 3

HEERA Output processor and database:

- Produce formatted output tables and charts

Figure 27: HEERA modelling framework

6.2 Database design

The interactions between the representative blocks of tables, queries and forms that are incorporated in the three modules of Figure 27 are shown in Figure 28. In the final database design diagrams the interactions between the individual tables, queries and forms of these blocks are shown. These are not given in this report.

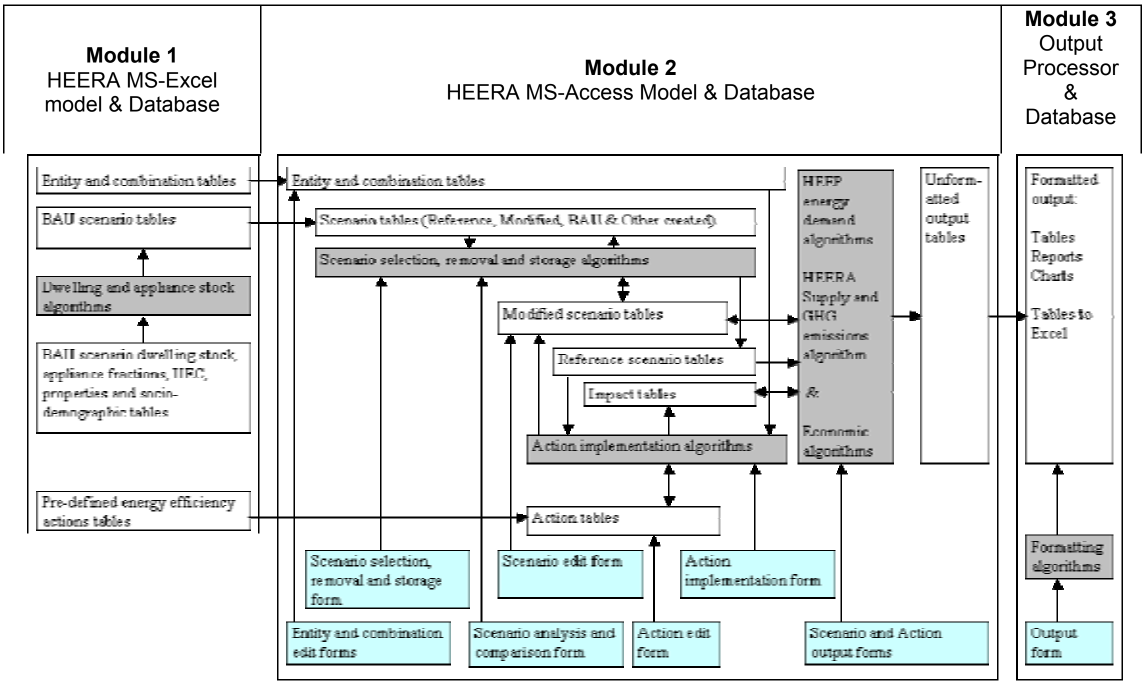


Figure 28: HEERA flow diagram with representative tables, algorithms and forms

6.3 HEERA Model

The HEERA model is based on information about the number of energy-using appliances in a dwelling, e.g. fridges and freezers, towel rails, dehumidifiers and washing machines to mention a few. How often are they used? An oven may, for instance, be used only occasionally. High-efficiency wood burners replace old wood burners. These changes and replacements have a considerable impact on energy consumption. The same applies to other energy-using appliances. The relationships, variables and drivers that determine the stocks and energy demand of the energy-using appliances are incorporated into the HEERA model.

The energy consumption of appliances is the product of the appliance stock and the energy intensity, i.e. the energy consumption per unit appliance. Sections 6.3.3 show that the stocks of dwellings and the most important residential appliances can be determined from official historic and projected statistics. Such statistics are not available for the energy intensity, i.e. the energy consumption per unit appliance. At best the national and regional energy demand for the residential sector is provided by official Ministry for Economic Development (MED) surveys.

However, in the HEERA model the effects of occupant socio-economic and demographic characteristics and behaviour should be reflected in the appliance energy intensities. This means that the space heating, water heating, cooking, lighting, refrigeration, laundry and electrical appliance models have to provide the *end-use energy demand per dwelling* from which the appliance energy intensities can be calculated with the help of appliance stocks per dwelling. These energy demand models are derived from literature sources and with the help of the HEEP measurements.

6.3.1 Basic quantities and relationships

A stock model formulation of energy demand is used in HEERA. In this formulation the total energy demand for the residential sector is described in terms of energy consuming units (appliances) and variables that allow the time-dependent calculation of the energy demand and of the impact of energy efficiency measures on the energy consumption. This is possible at different levels of aggregation, corresponding to different levels of available data and refinement of energy efficiency measures.

The total delivered end-use energy consumption (DEC) per year at time *t* by all appliances (technologies) is given by the energy demand function Equation 1:

$$E(t) = \sum_r \sum_z \sum_h \sum_i \sum_d \sum_a \sum_e \sum_b E_{rzhidaeb}(t)$$ **Equation 5 (1)**

$E_{rzhidaeb}(t)$ is the annual DEC at year *t* of appliance type *a*, belonging to a configuration described by a particular geographic region *r*, activity *z*, end-use *d*, energy type *e* and combination *b*, surrounded by a thermal envelope *h* with insulation level *i*.

The indices *r, z, h, i, d, a, e* and *b* specify the geographical, economic, environmental and physical configuration of the appliance. All the indices and variables are assumed discrete, with one year as the unit of time.

The DEC is defined as the energy delivered to an appliance, as compared to the useful energy output (UEO) of the appliance. The efficiency factor η accounts for appliance energy conversion losses and the DEC is obtained from the UEO and η by: DEC = UEO/η.

The function $E_{rzhidaeb}(t)$ in equation (1) can be expressed in the stock model formulation as:

$$E_{rzhidaeb}(t) = N_{rzhidaeb}(t) Q_{rzhidaeb}(t)$$ **Equation 6 (2)**

where:

$N_{rzhidaeb}(t)$ = appliance population of type *a* at time *t*, belonging to the configuration specified by its indices

$Q_{rzhidaeb}(t)$ = energy intensity, i.e. annual DEC per unit of appliance type *a* at time *t*, belonging to the configuration specified by its indices.

The appliance population in equation (2) can be further expanded as:

$$N_{rzhidaeb}(t) = p_{rz}(t) n_{rzhi}(t) n_{rzhidaeb}(t)$$ **Equation 7 (3)**

where:

$p_{rz(t)}$ = sector activity, i.e. some economic quantity *z* that characterises the energy use of the appliance in region *r* (see Section 6.3.3)

$N_{rzhi}(t)$ = envelope intensity, i.e. thermal envelope stock in terms of thermal envelopes per unit activity for the indices *r, z, h* and *i* and variable *t* (see Section 6.3.4)

$n_{rzhidaeb}(t)$ = appliance intensity, i.e. appliance stock in terms of stock per unit envelope for the indices *r, z, h, i, d, a, e* and *b* and variable t.

The change in the population of an appliance at time *t* is the difference between annual addition and removal terms by the appliance vintage stock model.

In this formulation the effect of user operation is contained in the energy intensity factor $Q_{rzhidaeb}(t)$. Since the energy intensity is determined from the appliance stocks and energy demand per dwelling, the effect of user operation is implicit through the energy demand models.

Space-heating simulation procedures and models such as ALF3 (Stoecklein and Bassett, 2000) and EnergyPlus calculate the heating load required to maintain the difference between the set temperature inside a thermal envelope and that of the environment, using the thermal properties and configuration of the thermal envelope. Such models could therefore be used to calculate the total annual heating energy of all the appliances inside a given environment and envelope configuration (e.g. a building in a given region), such that the inside temperature of the envelope is maintained at the set point temperature of the envelope by a specified heating schedule.

A specific appliance type *a* used inside the envelope would have an annual delivered energy consumption per unit appliance of $Q_{rzhidaeb}(t)$, belonging to the configuration specified by its indices, with $N_{rzhidaeb}(t)$ appliances converting delivered energy of type *e* into heating energy with efficiency η_{aeb}. In order to use the envelope heating energy (u_{rzhi}) as determined by a building simulation model to calculate the $Q_{rzhidaeb}(t)$ for an appliance, the fraction $\varphi_{rzhidaeb}(t)$ of u_{rzhi} contributed by appliance type *a* must be known. Then:

$$Q_{rzhidaeb} = \frac{\varphi_{rzhidaeb}(t) u_{rzhi}}{\eta_{aeb} N_{rzhidaeb}(t)}$$ **Equation 8 (6)**

6.3.2 Geographic region

The geographic region (r = 1, 2 … R) specifies where the appliance is employed and affects the environmental temperature, i.e. the degree-days required to heat a thermal envelope to a specified temperature. In the Approved Documents to Clause H1 of the NZBC, the regions are specified by the following three climate zones (Standards New Zealand NZS 4218: 1996 and NZS 4243: 1996):

- Zone 1: Thames-Coromandel District, Franklin District and all districts north of these
- Zone 2: the remainder of the North Island excluding Taupo and Ruapehu Districts and the northern part of Rangitikei District
- Zone 3: the remainder of the country, being the South Island and the central North Island excluded from Zone 2.

The insulation requirements for dwellings are the same for Zones 1 and 2, but higher insulation (R-values) are required for Zone 3. In rough terms, the thickness of insulating material for dwellings in Zone 3 is approximately 30 percent greater than for Zones 1 and 2.

In order to analyse energy consumption and the impact of energy efficiency measures in a meaningful way, however, HEERA stakeholders require a finer regional specification based on Regional Council and, in some cases, Territorial Authority boundaries. Such boundaries also make sense since electricity and gas supply statistics are available at the Regional Council level through Information Disclosure Statistics from suppliers.

Energy-use statistics for Territorial Authority analysis have to be estimated by splitting up the Regional Council data by means of an economic statistic that is related to energy use at the Territorial Authority level. The chosen statistic is the stock of occupied dwellings, since this is directly proportional to residential energy use and is also used as sector activity in HEERA.

An important consideration for developing the capability to estimate the energy use at the Territorial Authority level is the ability it provides to combine the Territorial Authorities into Regional Council groupings of choice, as required by the HEERA stakeholders.

The basic HEERA regional boundaries are therefore chosen as that of the following 16 Regional Councils, given in Table 30 in terms of their Territorial Authority combinations,[10]

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[10] DC = District Council, CC = City Council
Local Government New Zealand: www.lgnz.co.nz/lg-sector/maps/index.html accessed 6 Dec 2004

HEERA Regional ID (Regional Council)	Territorial Authority Combination
Northland	Far North DC, Whangarei DC, Kaipara DC
Auckland	Rodney DC, North Shore CC, Waitakere CC Auckland CC, Manukau CC, Papakura DC, Franklin DC (North)
Waikato	Franklin DC (South), Waikato DC, Hamilton CC, Waipa DC, Otorohanga DC, Waitomo DC, Thames-Coromandel DC, Hauraki DC, Matamata-Piako DC, South Waikato DC, Taupo-West DC, Rotorua DC (South West)
Bay of Plenty	Taupo-North East DC, Tauranga DC, Whakatane DC, Kawerau DC, Western Bay of Plenty DC, Opotiki DC, Rotorua DC (North East)
Gisborne	Gisborne DC
Hawkes Bay	Taupo DC (South East), Wairoa DC, Hastings DC, Napier CC, Central Hawkes Bay DC, Rangitikei DC (North East)
Taranaki	New Plymouth City DC, Stratford DC (West), South Taranaki DC
Manawatu-Wanganui	Stratford DC (East), Ruapehu DC, Wanganui DC, Rangitikei DC (South West), Manawatu DC, Tararua DC, Palmerston North CC, Horowhenua DC
Wellington	Kapiti Coast DC, Masterton DC, Carterton DC, South Wairarapa DC, Upper Hutt CC, Lower Hutt CC, Wellington CC, Porirua City CC
Marlborough	Marlborough DC
Nelson	Nelson CC
Tasman	Tasman DC (North East)
West Coast	Tasman DC (South West), Buller DC, Grey DC, Westland DC
Canterbury	Kaikoura DC, Hurunui DC, Waimakariri DC, Christchurch CC, Banks Peninsula DC, Selwyn DC, Ashburton DC, Timaru DC, Mackenzie DC, Waimate DC, Waitaki DC (North West)
Otago	Waitaki DC (South East), Central Otago DC, Queenstown-Lakes DC, Dunedin CC, Clutha DC
Southland	Southland DC, Gore DC, Invercargill CC

Table 30: HEERA 16 regions – Regional Councils and Territorial Authorities

6.3.3 Sector activity

The sector activity with index (z = 1, 2 … Z) is expressed by the quantity $p_{rz}(t)$ in Equation (3). It measures the energy-dependent economic activity of the residential sector by means of an inflation-independent physical quantity such as dwelling stock or floor area. The purpose of expressing the energy-using appliance stock as a fraction of the sector activity in Equation (3) is to base the projection and interpolation of the energy-dependent appliance stocks and energy intensities on an acknowledged economic-growth index.

For scenario stock models such as HEERA, the sector activity is the central quantity that drives the projection and interpolation of other energy-dependent data. Choosing as sector activity an economic quantity that affects all other energy-dependent data in a sector, and for which reliable economic projections are available, is necessary to the success of the HEERA model.

HEERA requires data about regional appliance stock levels. This is supplied in the form of household appliance ownership statistics and energy consumption statistics per household by Statistics NZ (Statistics NZ, 2001). Furthermore, historic stocks of existing (Statistics NZ, 2001) and new (Statistics NZ, 1998, 2003) regional dwellings and projected households (Statistics NZ, 2004) are available from Statistics NZ. This combination of dwelling-related statistics makes the regional occupied permanent private dwelling stock the logical choice as residential sector activity.

The NZ Census defines (Statistics NZ, 2002a, 2002b), a private dwelling as accommodating a person or a group of people, but as not available to the public. Permanent private dwellings include houses and flats, residences attached to a business or institution, and bachs, cribs and huts. Caravans, cabins, tents and other makeshift dwellings that are the principal or usual residence of households are classified as temporary private dwellings.

Census statistics over the historic period covered by HEERA are available for the occupied permanent private dwelling stock at national, Regional Council, Territorial Authority and even mesh block level. No projections of the occupied permanent private dwelling stock exist.

However, Statistics NZ provides projections of the household stock at the Territorial Authority, Regional Council and national levels up to 2021. A household is defined (Statistics NZ, 2002a, 2002b) as either one person who usually resides alone or two or more people who usually reside together and share facilities (such as eating facilities, cooking facilities, bathroom and toilet facilities, a living area).

From the definitions of occupied permanent private dwellings and households, it seems reasonable to equate occupied permanent private dwellings and households for projection purposes. The term dwelling has been adopted for both concepts.

In the same way as with appliance stock, the regional dwelling stock at time *t* also is the difference between annual addition and removal terms which can be described by a dwelling vintage stock model. The following dwelling vintage stock model is an adaptation of the appliance vintage stock model developed for the UK's DECADE stock model (Boardman et al, 1995).

6.3.3.1 Dwelling vintage stock model

In the dwelling vintage stock model the stock of dwellings in a region can be presented as in Figure 29 and expressed by Equation (7).

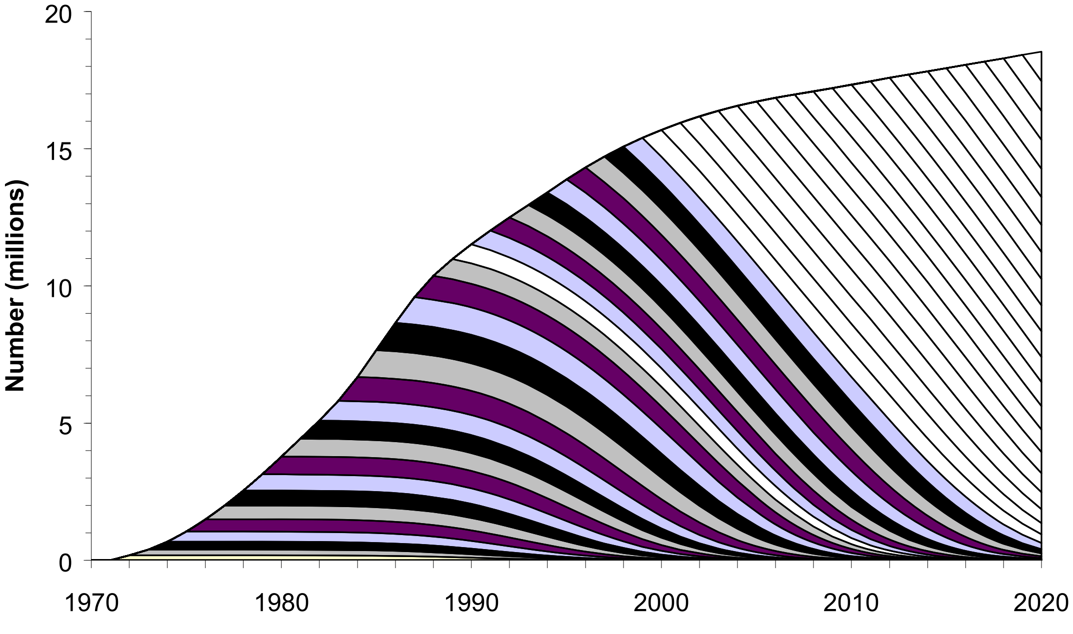

Figure 29: Contribution of new dwellings to the stock of dwellings

$$Stock(k) = \sum_{k-start}^{End} \sum_{j=start}^{End} New(j) \times Remain(j,k) - Removed(j)$$ **Equation 9 (7)**

Stock(k) = Estimated number of dwellings in year *k*

New(j) = Number of new dwellings built in year *j*

Remain(j,k) = Fraction of dwellings built in year *j* remaining by year *k*

Removed(j) = Number of dwellings removed by policy measures in year *j*

Start = First year of period over which the model operates

End = Last year of period over which the model operates

In Equation (7) it is assumed that dwellings are removed by retirement according to the *Remain(j,k)* factor, unless removed by some policy mechanism through the *Removed(j)* term. Dwellings that are removed by the *Remain(j,k)* factor could be replaced with the same type of dwelling, but this replacement is treated as a new dwelling.

The *Remain(j,k)* factor can be described in terms of statistical terminology (Hastings, 1974), where it represents the survival function, i.e. the probability of stock surviving to a specified year. The distribution function *F(j,k) = 1-Remain(j,k)* is the probability of retirement *by* that year. The probability of stock retiring *in* that year is the probability density of *F(j,k)*, i.e. the derivative of *F(j,k)* with reference to time, designated by Δ*Remain(j,k)*.

The *Remain(j,k)* factor can be represented by a number of functions, e.g. step, linear, exponential, logistic, normal or extreme value function. *Remain(j,k)* depends on the mean lifetime L of a dwelling and in the case of the logistic, normal and smallest extreme value distributions, also on the standard deviation σ about the mean lifetime. In the case of the logistic and smallest extreme value functions, the lifetime and standard deviation are expressed in terms of parameters that are defined for these functions in the Appendix. The mean lifetime is obtained by weighting the lifetime with Δ*Remain(j,k)* and is given by:

$$L = \frac{\sum_{j=start}^{End}}{\sum_{j=start}^{End}} \frac{Lifetime(j) \times \Delta Remain(j,End)}{\Delta Remain(j,End)}$$ **Equation 10 (8)**

A typical dwelling survival function is used by the Dwelling Stock Model in the NEMS Residential Model (Office of Integrated Analysis and Forecasting, 2003). This Dwelling Stock Model calculates dwelling stock additions, survival, and retirements in order to produce the total dwelling stock by vintage, type and region. Dwelling units are removed from the dwelling stock at a constant rate over time. The annual survival rates, *a,* for dwelling stock types are assumed by the model to be 0.996 for single-family homes, 0.993 for multi-family homes and 0.965 for mobile homes. From the expression ln *a* = -1/L for the exponential function of the Appendix, the mean lifetimes are respectively 249, 142 and 28 years. In the United Kingdom, the lifetimes of the building components of dwellings have been reported by the English House Condition Survey. The mean lifetime of the major residential components is 48 years (Bates et al, 2002 and OPDM, 2003).

The mortality of New Zealand dwelling stock has been investigated by Johnstone (1994), who developed a dynamic dwelling mortality model based on a model by Gleeson (Gleeson, 1985) and New Zealand National Housing Commission dwelling records over a period from 1860 to 1980. The most important aspects and results of this deterministic model are:

1. The model is driven externally by a series of net gain variables and internally by endogenous probability of loss variables, which are amplified by predetermined expansion rates of dwelling stock.
2. The mortality model simulates dwelling losses from individual surviving dwelling cohorts over each time interval, where all these cohorts contribute to the total dwelling loss of a particular future time interval.
3. The mortality of a dwelling cohort upon entry determines the dwelling life expectancy:
    - Under a hypothesis of *static mortality*, dwelling cohorts are exposed to the same mortality regime, resulting in the cohorts having the same life expectancy.
    - Under *variable mortality*, dwelling cohorts are exposed to mortality regimes that change over time, resulting in dwelling cohorts having different life expectancies upon entry.
    - Under *dynamic mortality*, the mortality regimes of all cohorts change simultaneously over a period due to economic circumstances, resulting in the life expectancy of dwelling cohorts changing during their lifetimes.
4. The main findings are that the New Zealand dwelling stock has been exposed to a dynamic mortality regime which is a function of age and the expansion rate of the dwelling stock. As a result of fluctuations in the expansion rate, *each dwelling cohort has been exposed to different regimes of mortality*.
5. About 50% of dwellings have been lost from each dwelling cohort by the age of 90 years and the distribution of losses follows a bell shape skewed to the left.

In principle the HEERA dwelling vintage stock model could be used to model the New Zealand dwelling stock in the same way as Johnstone's model (1994) under the following conditions:

- A smallest extreme value survival function is assumed for *Remain(j,k)*, i.e. one having a bell-shaped probability density distribution Δ*Remain(j,k)* skewed to the left.
- The lifetime and standard deviation of Δ*Remain(j,k)* determine the mortality of dwelling cohorts entering the dwelling stock, and both the lifetime and standard deviation depend on the expansion rate of the dwelling stock at time of entry.
- If economic conditions change the expansion rate at any time, the lifetimes and standard deviations of all dwelling cohorts are adjusted accordingly.

How the restrictions of information availability in New Zealand affect the extent to which the HEERA dwelling vintage stock model can be used for the HEERA BAU scenario, is discussed in sections 6.3.3.2 and 6.3.3.3, which describe the national and regional dwelling stock models.

6.3.3.2 National dwelling stock model

The New Zealand dwellings that are considered in HEERA for sector activity purposes are assumed to be permanent domestic dwellings occupied by private households. These are defined by Statistics NZ for the Census of Population and Dwellings purposes (Statistics NZ, 2002a, 2002b) as "occupied permanent private dwellings". It includes: separate houses, two or more houses or flats joined together, flats or houses joined to a business or shop, and bachs, cribs and other holiday homes. It excludes non-private dwellings (e.g. hotels and motels), temporary dwellings (e.g. tents and caravans) and unoccupied dwellings.

This definition of dwellings corresponds exactly with that used for the Census dwelling categories. However, only projections of *households* for a range of birth, mortality and immigration scenarios are available from Statistics NZ's “Subnational Household Projections” (Statistics NZ, 2004). To enable the use of the Statistics NZ projection data for HEERA sector activity purposes, households are therefore equated with occupied permanent private dwellings and categorised as dwellings.

The number of dwellings within Regional Council and Territorial Authority boundaries is available as five-yearly Census time-series statistics for the period 1878 to 2001 (Statistics NZ, 2001). Projections at the Regional Council level for the medium birth, mortality and immigration growth scenarios are available at five-yearly intervals for the period 2001 to 2021 (Statistics NZ, 2004). Annual additions to the dwelling stock in Regional Councils and Territorial Authorities are available from Statistics NZ's Building Consents (e.g. Statistics NZ, 2003). Annual additions to the *national* dwelling stock are available from 1974 to 2003 (e.g. Statistics NZ, 1998, 2003).

The dwelling vintage stock model described in the previous section requires for its use the annual new dwelling stock, the new dwelling lifetime and the standard deviation of the probability of retiring at a specified year after its erection. This allows the calculation of the net annual dwelling stock as the sum of the annual additions remaining at the specified year. Alternatively, if the net annual dwelling stock, the annual lifetimes and standard deviations are known, the annual dwelling stock additions can be calculated. Since the historic and projected dwelling stock for the medium growth New Zealand scenario is available from Statistics NZ, the alternative method is employed as follows to determine the annual new dwelling stock for the business-as-usual (BAU) residential HEERA dwelling stock model:

1. A logistic growth function is fitted to the five-yearly Census statistics (1878 to 2001) and the subnational household projections (2001 to 2021) to estimate annual net dwelling stock over the period 1850 to 2070 (Figure 30):

$$2{,}500{,}000 \times (1 - 1/(1 + esp(0.286735617 \times yr - 57.2301901301)), \quad R^2 = 0.9982$$

Equation 11

(10)

   The logistic smoothing distribution function is used for estimating New Zealand dwelling stock instead of Census statistics, even when these are available. This is a consequence of the need for smoothly varying annual new dwelling stocks by the dwelling stock model, since the model is used for interpolation and extrapolation purposes. The effect on the calculation of new dwelling stock with the dwelling vintage stock model when using the logistic smoothing function is illustrated in Figure 31.

2. According to the findings of Johnstone, the New Zealand dwelling stock has been exposed to a dynamic mortality regime which is a function of age and the expansion rate of the dwelling stock. The expansion rate for a given year is defined by the ratio of that year's net dwelling stock to that of the previous year. The lifetime and standard deviation for a given year is calculated by multiplying the lifetime and standard deviation of the previous year with the expansion rate and a scale factor. These scale factors are optimised by minimising the sum of the squares of the deviation between the calculated and surveyed new dwelling stock over the period 1974 and 2003, a period for which new dwelling stock records are available from Building Consent records.

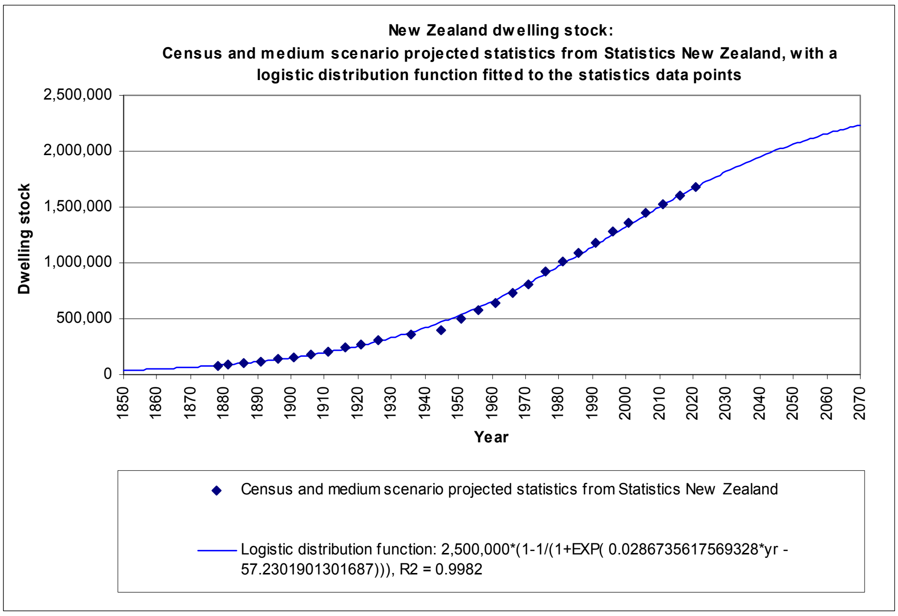

Figure 30: Net dwelling stock growth over the period 1850 to 2070

3. Subsequently the relationships Equation (7) above and Equation (A.1) in the Appendix are used to calculate the smoothed annual new dwelling stock numbers from the net dwelling stock (Figure 31). The calculation uses the net dwelling stock logistic distribution function and a survival function based on a smallest extreme value retirement probability function that is skewed to the left. This incorporates the findings of Johnstone for the dwelling stock over the period 1860 to 1980.

   Annual lifetimes and standard deviations are obtained by multiplying a previous year's lifetime and standard deviation with an optimised adjustment factor depending on the annual dwelling expansion rate.

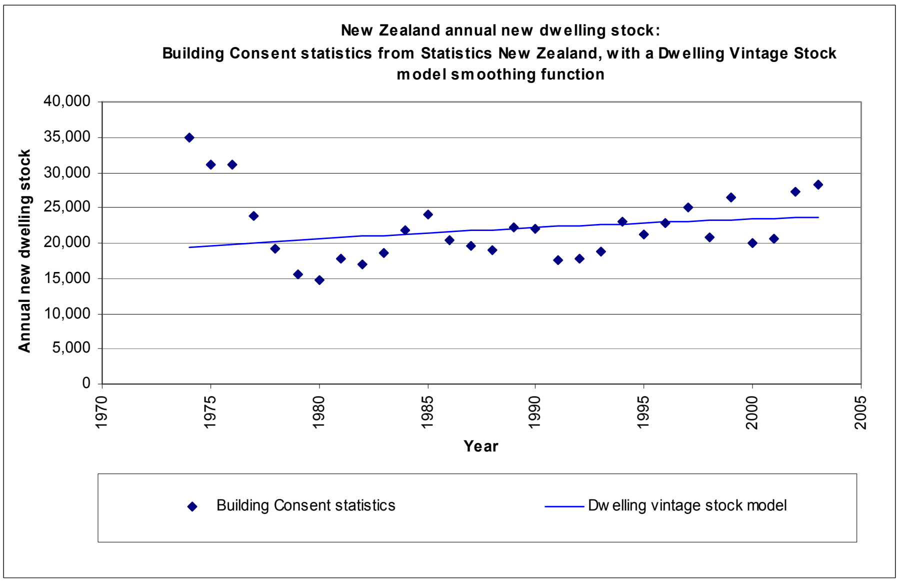

Figure 31: Building consents (1974 to 2003) compared to vintage stock model

The new dwelling survival function is based on smallest extreme value distribution and probability density functions with an average mean lifetime and standard deviation of 95 years and 25 year respectively. Figure 32 also illustrates the smallest extreme value survival and Figure 33 illustrates the probability density functions used in the dwelling vintage stock model.

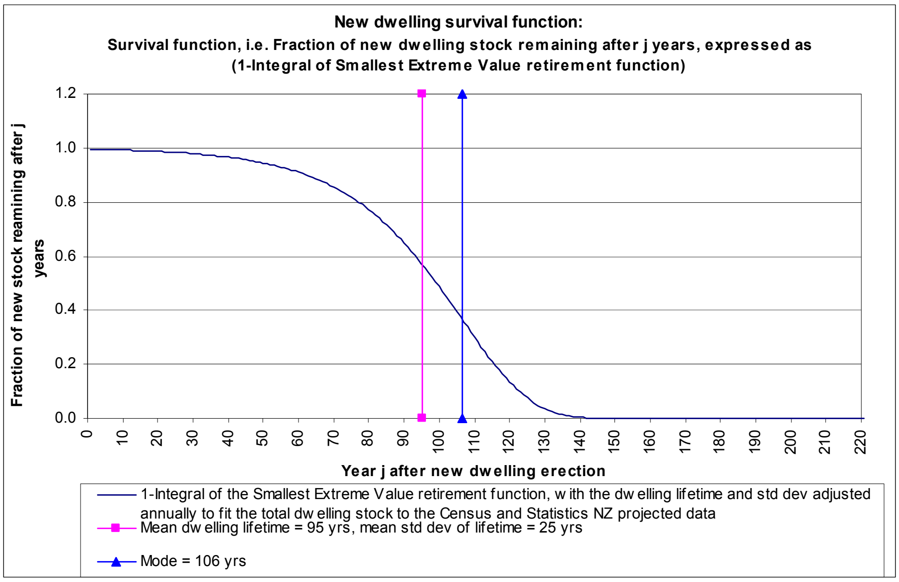

Figure 32: New dwelling survival function

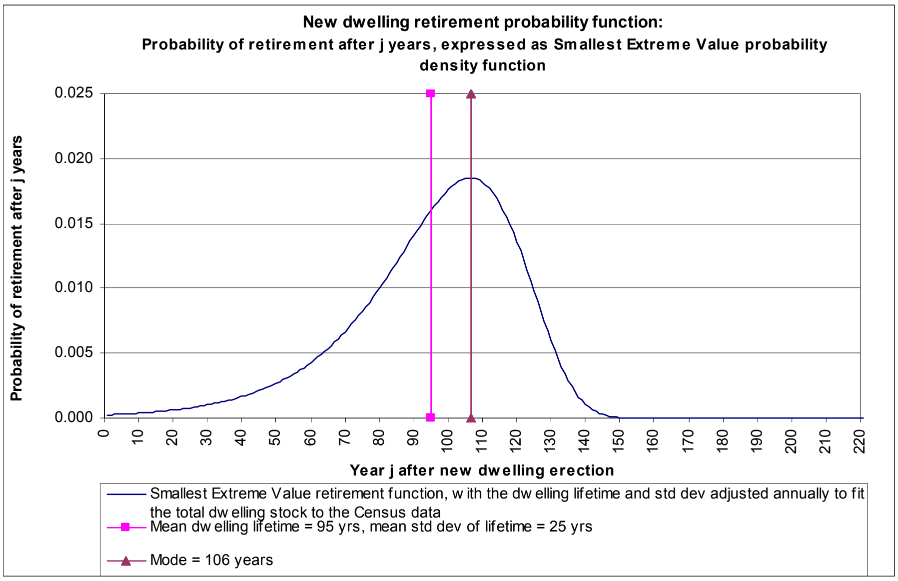

Figure 33: Probability of new dwelling stock retirement function

6.3.3.3 Regional dwelling stock model

The regional dwelling stock model describes how the national dwelling stock of Section 6.3.3.2 is distributed among the HEERA regions. This model is to be developed during the 2004/05 year

6.3.4 Thermal envelope and envelope intensity

The thermal envelope index (h = 1, 2 … H) specifies the thermal envelope that surrounds an appliance and depends on the economic sector in which it functions. For the residential sector it is chosen as dwelling type. Since it is possible to categorise dwellings in terms of their overall insulation level, energy efficiency measures that influence the thermal envelope index would influence the insulation level indirectly through changes to the dwelling stock. The choice and range of dwelling types therefore have important consequences for the application of energy efficiency measures.

The quantity $n_{rzhi}(t)$ in Equation (3) is the envelope intensity, i.e. envelopes per unit activity for the indices r, z, h and i. By defining thermal envelopes as dwellings, the envelope intensity is expressed as the dwelling intensity, i.e. dwellings of a specified type per unit activity. Since the activity $p_{rz}(t)$ is the sum of all dwelling types for a region, the dwelling intensity is expressed as the fraction of the total dwelling stock in a region.

The New Zealand dwelling stock is grouped into a number of basic types (Table 31) that represent different levels of thermal insulation for each region and therefore different levels of energy consumption by appliances in that region. The dwelling types of Table 31 represent the minimum thermal insulation levels required by the NZBC H1/AS1 for each zone and construction method. Revisions to the NZBC may add further dwelling types.

Dwelling type	Description
Uninsulated	Wood frame, wood floor: Pre-1978 NZBC: Clause H1. Uninsulated
Insulated roof	Wood frame, wood floor: Pre-1978 NZBC: Clause H1. Insulated roof
NZBC1978	Wood frame, wood or concrete floor: Rev 1978 of the NZBC: Clause H1
NZBC2000Z1	Wood frame, wood or concrete floor: Rev 2000 of the NZBC: Clause H1, Zone 1
NZBC2000Z2	Wood frame, wood or concrete floor: Rev 2000 of the NZBC: Clause H1, Zone 2
NZBC2000Z3	Wood frame, wood or concrete floor: Rev 2000 of the NZBC: Clause H1, Zone 3
Super-insulated	Wood frame, concrete floor: Solar and super-insulated, full double glazing
NZ average	Wood frame, wood or concrete floor. NZ weighted mean insulation specifications
Unspecified	Unspecified thermal envelope

Table 31: Basic dwelling types for categorising New Zealand dwelling stock

These basic dwelling types can be extended to describe the dwelling stock in more detail, as shown in Table 32.

Dwelling type	Thermal insulation specification
Uninsulated	Frame wall, Suspended floor: Pre-1977 NZBC: Clause H1. Uninsulated, i.e. Insulation: Roof: R0.5, Wall: R0.5, Floor: R0.5, Windows: Single glaze R0.18, Infiltration rate: 0.75 ACH
Roof insulated	Frame wall, Suspended floor: Pre-1977 NZBC: Clause H1. Roof insulated, i.e. Insulation: Roof: R1.9, Wall: R0.5, Floor: R0.5, Windows: Single glaze R0.18, Infiltration rate: 0.75 ACH
NZBC1977FrameSuspendSG	Frame wall, Suspended floor: Rev 1977 NZBC: Clause H1 Insulation: Roof: R1.9, Wall: R1.5, Floor: R1.3, Windows: Single glaze R0.18, Infiltration rate: 0.50 ACH
NZBC1977FrameSlabSG	Frame wall, Slab floor: Rev 1977 NZBC: Clause H1 Insulation: Roof: R1.9, Wall: R1.5, Floor: R2.0, Windows: Single glaze R0.18, Infiltration rate: 0.50 ACH
NZBC2000Z1FrameSuspendSG	Frame wall, Suspended floor: Rev 2000 NZBC: Clause H1, Zone 1 Insulation: Roof: R1.9, Wall: R1.5, Floor: R1.3, Windows: Single glaze R0.18, Infiltration rate: 0.50 ACH
NZBC2000Z1SolidSuspendSG	Solid wall , Suspended floor: Rev 2000 NZBC: Clause H1, Zone 1 Insulation: Roof: R3.0, Wall: R0.6, Floor: R1.3, Windows: Single glaze R0.18, Infiltration rate: 0.50 ACH
NZBC2000Z1FrameSlabSG	Frame wall, Slab floor: Rev 2000 NZBC: Clause H1, Zone 1 Insulation: Roof: R1.9, Wall: R1.5, Floor: R2.0, Windows: Single glaze R0.18, Infiltration rate: 0.50 ACH
NZBC2000Z1SolidSlabSG	Solid wall, Slab floor: Rev 2000 NZBC: Clause H1, Zone 1 Insulation: Roof: R3.0, Wall: R0.6, Floor: R2.0, Windows: Single glaze R0.18, Infiltration rate: 0.50 ACH
NZBC2000Z2FrameSuspendSG	Frame wall, Suspended floor: Rev 2000 NZBC: Clause H1, Zone 2 Insulation: Roof: R1.9, Wall: R1.5, Floor: R1.3, Windows: Single glaze R0.18, Infiltration rate: 0.50 ACH
NZBC2000Z2SolidSuspendSG	Solid wall, Suspended floor: Rev 2000 NZBC: Clause H1, Zone 2 Insulation: Roof: R3.0, Wall: R0.6, Floor: R1.3, Windows: Single glaze R0.18, Infiltration rate: 0.50 ACH
NZBC2000Z2FrameSlabSG	Frame wall, Slab floor: Rev 2000 NZBC: Clause H1, Zone 2 Insulation: Roof: R1.9, Wall: R1.5, Floor: R2.0, Windows: Single glaze R0.18, Infiltration rate: 0.50 ACH
NZBC2000Z2SolidSlabSG	Solid wall, Slab floor: Rev 2000 NZBC: Clause H1, Zone 2 Insulation: Roof: R3.0, Wall: R0.6, Floor: R2.0, Windows: Single glaze R0.18, Infiltration rate: 0.50 ACH
NZBC2000Z3FrameSuspendSG	Frame wall, Suspended floor: Rev 2000 NZBC: Clause H1, Zone 3 Insulation R-values: Roof: 2.5, Wall: 1.9, Floor: 1.3, Windows: Single glaze R0.18, Infiltration rate: 0.50 ACH
NZBC2000Z3SolidSuspendSG	Solid wall, Suspended floor: Rev 2000 NZBC: Clause H1, Zone 3 Insulation R-values: Roof: R3.0, Wall: R1.0, Floor: 1.3, Windows: Single glaze R0.18, Infiltration rate: 0.50 ACH
NZBC2000Z3FrameSuspendDG	Frame wall, Suspended floor: Rev 2000 NZBC: Clause H1, Zone 3 Insulation R-values: Roof: 2.5, Wall: 1.9, Floor: 1.3, Windows: Double glaze R0.33, Infiltration rate: 0.50 ACH
NZBC2000Z3SolidSuspendDG	Solid wall, Suspended floor: Rev 2000 NZBC: Clause H1, Zone 3 Insulation R-values: Roof: R3.0, Wall: R1.0, Floor: 1.3, Windows: Double glaze R0.33, Infiltration rate: 0.50 ACH
NZBC2000Z3FrameSlabSG	Frame wall, Slab floor: Rev 2000 NZBC: Clause H1, Zone 3 Insulation R-values: Roof: 2.5, Wall: 1.9, Floor: 2.0, Windows: Single glaze R0.18, Infiltration rate: 0.50 ACH
NZBC2000Z3SolidSlabSG	Solid wall, Slab floor: Rev 2000 NZBC: Clause H1, Zone 3 Insulation R-values: Roof: R3.0, Wall: R1.0, Floor: 2.0, Windows: Single glaze R0.18, Infiltration rate: 0.50 ACH
NZBC2000Z3FrameSlabDG	Frame wall, Slab floor: Rev 2000 NZBC: Clause H1, Zone 3 Insulation R-values: Roof: 2.5, Wall: 1.9, Floor: 2.0, Windows: Double glaze R0.33, Infiltration rate: 0.50 ACH
NZBC2000Z3SolidSlabDG	Solid wall, Slab floor: Rev 2000 NZBC: Clause H1, Zone 3 Insulation R-values: Roof: R3.0, Wall: R1.0, Floor: 2.0, Windows: Double glaze R0.33, Infiltration rate: 0.50 ACH
Superinsulated	Frame wall, Slab floor: Solar & Superinsulated Insulation R-values: Roof: 3.5, Wall: 2.5, Floor: 2.0, Windows: Double glaze R0.33, Infiltration rate: 0.50 ACH
NZ average	Frame wall, Suspended or slab floor. Insulation R-values for roof, wall, floor and window: Weighted mean values for New Zealand
Unspecified	Unspecified thermal envelope

Table 32: Extended dwelling types used for categorising the NZ dwelling stock

Since the thermal envelopes are defined as dwellings, the envelope intensity is expressed as the dwelling intensity, i.e. dwellings of a specified type per unit activity. The activity p_{rz} (t) is the sum of all dwelling types for a region, and the dwelling intensity is therefore expressed as the fraction of the total dwelling stock in a region.

All new dwellings in a region have to conform to the NZBC energy efficiency performance requirement for that region – generally represented by the Acceptable Solution in the form of NZS 4218:1977P or NZS 4218:1996. Using the NZBC to specify dwelling types therefore makes it possible to use the dwelling vintage stock model to estimate the annual new dwelling stock of the dwelling type specified for that region. Figure 34 shows the New Zealand national dwelling stock, as estimated by the EERA dwelling stock model, for the dwelling types of Table 31. The dwelling types NZBC 2000Z1, NZBC 2000Z2 and NZBC 2000Z2 have been consolidated to the NZBC Rev 1996 Timber Floor and Concrete Floor types in Figure 34.

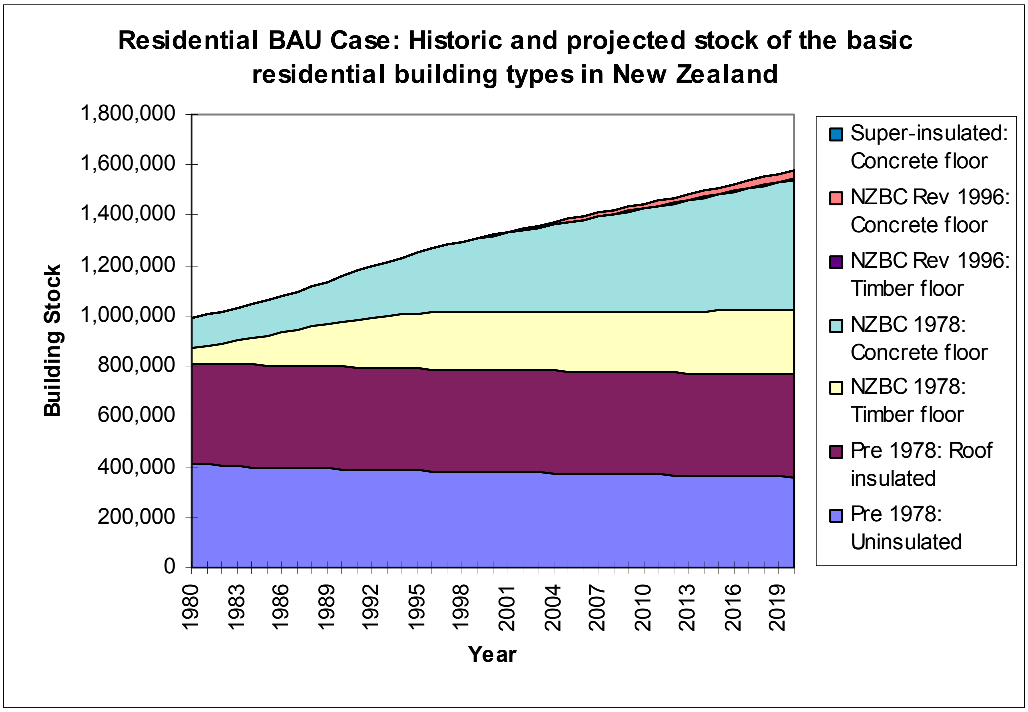

Figure 34: National dwelling stock by insulation level

6.4 Excel and Access database tables

The database information is organised in terms of records pertaining to scenarios, energy-efficiency actions and those independent of scenarios and energy-efficiency actions.

6.4.1 Scenario dependent data

The scenario and energy-efficiency dependent data is time-dependent and covers the period 1950 to 2050. In the HEERA BAU scenario, the historic period is from 1950 to the last available historic data point and from this point to 2050 contains projected data. Due to the fragmentary nature of some of the historic data, sometimes representing only a few disjointed years, interpolation of historic data is also required.

Scenarios contain energy use records for a wide range of appliances for all residential end-uses, where the total delivered end-use energy of a scenario is aggregated over appliance records. The energy use records are divided into dwelling, appliance fraction and energy intensity records.

In addition to energy use records, records characterising the thermal envelopes used in the scenario in terms of dimensions, thermal insulation, infiltration, thermal set point and heating schedule, and other miscellaneous records are required.

6.4.2 Energy-efficiency dependent data

Action records define all the implementation details of an energy-efficiency action unless the economic impact of the action is required, in which case records specifying the capital and annual costs of implementing the action are also needed.

6.4.3 Scenario independent and energy-efficiency independent data

These tables can be entity tables, tables joining entity indices such as supply to demand ratios and GHG emission ratios, energy prices, report specifications and references.

6.5 Graphic User Interface forms and VB procedures

Users interact with the HEERA Access model and database through forms, which act as the Graphic User Interface (GUI). Control objects on these forms are used to input data. In most forms these controls are connected to Visual Basic (VB) procedures which call macros that execute the algorithm queries.

6.6 Demonstration

Four scenarios were constructed and compared to explore what would happen to dishwasher electricity demand in Auckland if the household life stage changes linearly from ‘Working’ in 2004 to 100% ‘Retired’, ‘School’ and ‘Pre-school’ life stages in 2020. For all scenarios the household size (four people) and dishwasher appliance stock remain the same over the whole period. These scenarios were also used to demonstrate the HEERA Excel model and database in the HEEP Year 9 report.

7. WINTER TEMPERATURES

This section gives an overview of winter temperatures and explores some of the key influences. Winter is defined as the months of June, July and August, and evening is from 5.00 p.m. to 11.00 p.m.

7.1 Historical comparison

Prior to HEEP, the only national temperature measurements to be carried out in New Zealand were during the 1971/72 Household Electricity Survey (Statistics NZ, 1976). Table 33 compares, by region, the HEEP living room temperatures with the lounge temperatures for August-September 1971.

Aug-Sep temperatures °C	Northern North Island		Southern North Island		Christchurch		Southern South Island	
	HEEP 2001-2004	**1971**	**HEEP 1999, 2002-2004**	**1971**	**HEEP 2002**	**1971**	**HEEP 2003**	**1971**
Living room:								
Mean temperature	16.5	17.7	16.1	16.6	16.1	15.2	14.7	13.6
Standard deviation	0.1	-	0.2	-	0.3	-	0.5	-
95% Confidence interval	16.2-16.8	-	15.8-16.5	-	15.4 – 16.7	-	13.7-15.8	-
External:								
Mean temperature	11.9	12.0	9.3	11.0	10.3	9.3	7.3	8.6
Mean temperature difference	4.6	***5.7***	6.9	***5.6***	5.7	***5.9***	7.4	***5.0***
Sample size	112	98	74	64	34	69	30	64

Table 33: HEEP and 1971 descriptive temperatures by region

The 1971/72 temperature study found a strong consistency in the difference between inside and outside temperature (in ***bold italics*** in Table 33). The study concluded that 'in homes throughout New Zealand, rooms tend to be heated to certain levels above the surrounding outside air temperature, rather than to a universal absolute temperature level'.

This does not appear to be the case for the HEEP sample, with the temperature differences shown in Table 33 ranging from 4.6°C in the Northern North Island to 7.4°C in the Southern South Island. Table 33 suggests that excluding the Southern South Island, average living room temperatures are close to 16°C.

7.2 Climate

Figure 35 shows the mean evening living room and ambient temperatures by region from north to south. Figure 35 shows a trend from north to south, although it is not straightforward. There are statistically significant differences between the regions, but these are not only related to the climate.

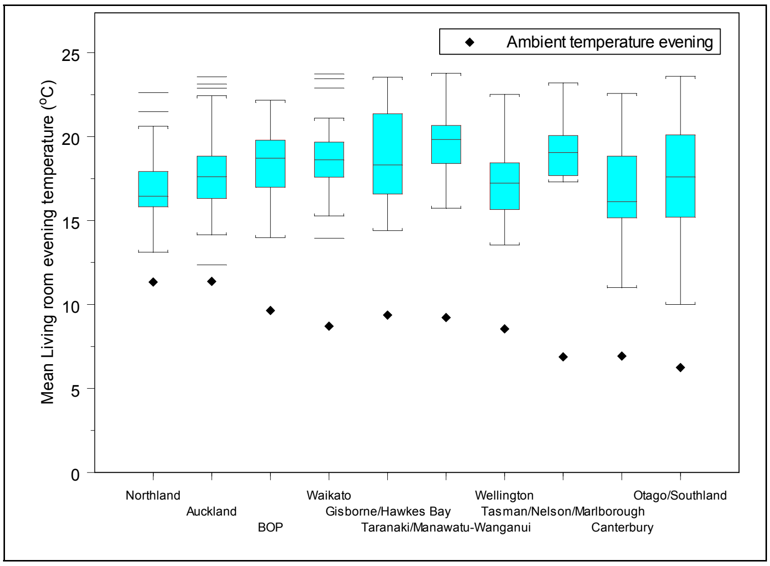

Figure 35: Mean winter evening living room and ambient temperature by Regional Council

Northland has a higher median ambient evening temperature (Figure 35 black diamonds) than Otago/Southland, with a heating season of over eight months. Houses in the north heat for a much shorter time than those in the south. They also generally have less efficient (open fires) and less powerful heaters.

There is a significant difference between the Regional Councils (p-value = 0.0000022).

There is also a general trend, shown in Figure 36, of decreasing overnight bedroom temperatures from north to south. This is expected, as most households do not heat bedrooms overnight, so the temperatures inside bedrooms should only be a few degrees above the external temperature.

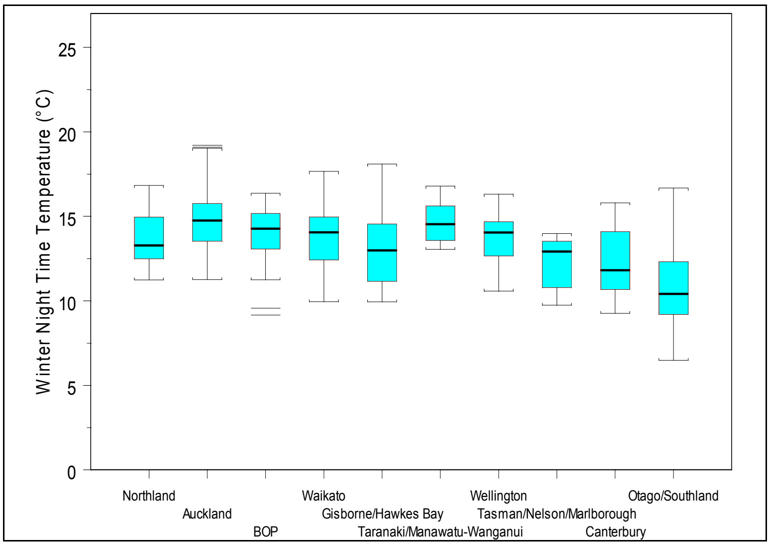

Figure 36: Mean winter night time bedroom temperature by Regional Council

7.3 Temperature distribution

The distribution of national winter evening living room temperatures can be seen in Figure 37. The mean and median temperature is 17.9°C.

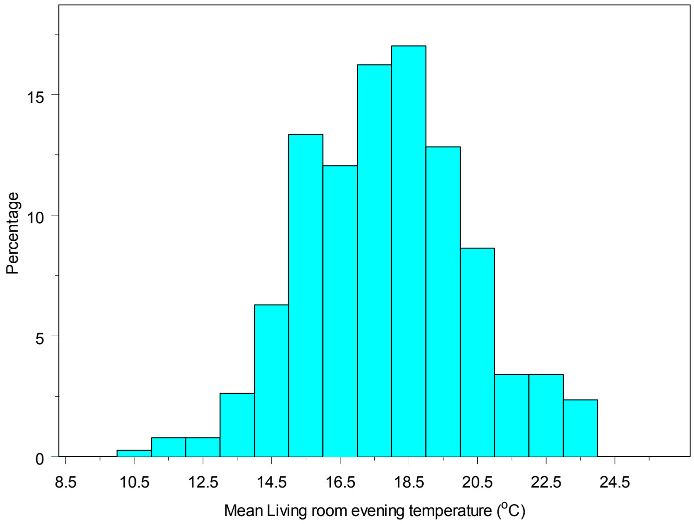

Figure 37:Distribution of winter evening living room temperatures

Table 34 gives mean winter temperatures for four different periods during the day for the living room, bedroom and ambient temperature. The time periods are:

- **Morning**: 7.00 a.m. to 9.00 a.m.
- **Day**: 9.00 a.m. to 5.00 p.m.
- **Evening**: 5.00 p.m. to 11.00 p.m.[11]
- **Night**: 12.00 p.m. to 7.00 a.m.

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[11] The hour from 11 pm to 12 pm is not included due to software limitations.

Room	Mean temperatures (°C) Morning	Day	Evening	Night
Living room	13.5	15.8	17.8	14.8
Bedroom	12.6	14.2	15.0	13.6
Ambient	7.8	12.0	9.4	7.6

Table 34: Mean temperatures: living room, bedroom and ambient

During the day, the bedroom is 2.2°C warmer than outside and the living room averages 3.8°C warmer than outside. These temperatures fail to achieve the WHO optimum indoor temperature range of between 18°C to 24°C (WHO 2003).

Morning is the coldest time inside the average house, although the coldest time outside is overnight. Evenings are warmest (this is also the most common heating time). Bedrooms are on average slightly colder than living rooms – at most there is a difference of 3.8°C which occurs during the evening. This is most likely caused by heating in the living room with typically very little or none in the bedrooms.

Table 34 can be used to explore the changes between different periods of the day for the average living room, bedroom and the mean external temperatures. The mean living room temperature increases during the morning and day periods, but drops in the evening and overnight. This is a slight delay compared to the ambient temperature, which drops between day and evening, and again between evening and night. During the day the ambient temperature peaks, but the peak living room temperature generally occurs during the evening period. The average peak temperature time in all houses is 5.48 p.m., and there is little regional variation.

Only 15% of houses heat bedrooms at night, but when coupled with small heat gains from occupants (and TVs, clock radios, pets etc) bedroom temperatures become closer to living room temperatures overnight and during the morning. During the day the temperature difference between the two rooms is 1.6°C.

7.4 Reported heating schedules by occupants

Heating schedules were reported by occupants when surveyed. Differences between regions and weekdays/weekends for daytime heating can be seen in Figure 38 which shows the percent of houses in each region that heat the living room for that part of the week. Not surprisingly, houses in colder climates (Southland/Otago, Central North Island etc) heat more during the day than houses in warmer climates, with more heating being used on weekends when occupants are more likely to be at home. A reason for the decrease in heating during the day for the Lower North Island and Wellington has yet to be determined. Preliminary comparisons of the daytime house occupancy and the heating schedule show no significant relationship.

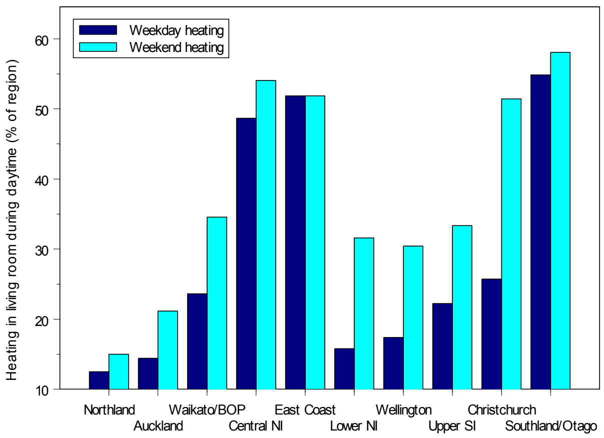

Figure 38: Living room daytime heating by region and weekday/weekend

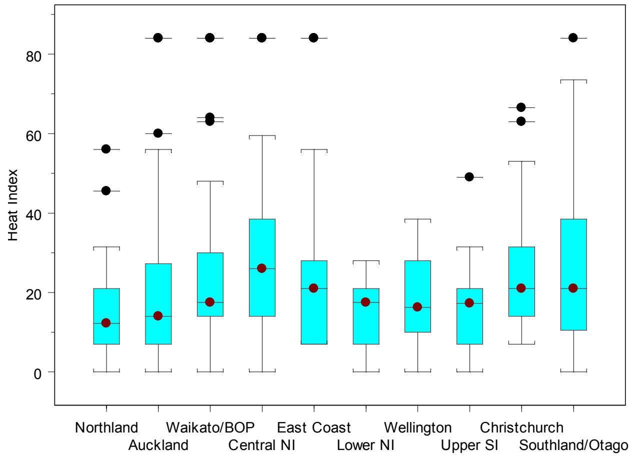

Figure 39: Heating index by region

The HEEP Year 7 report introduced the HEEP 'heating index' (Isaacs et al, 2003). In brief, the HEEP occupant survey asked for information on the times of heating (time of day and day of week) for three locations – the bedrooms, living and utility rooms. The weighted sum then forms the whole house heating index.

Figure 39 shows the heating index by region. The five houses at the maximum heating index of 84 reported heating the whole house 24 hours a day. A relationship can be seen between climate and the use of heating – unsurprisingly, the colder the climate the greater the use of heating.

Figure 40 shows that the houses in the South Island report that they are typically less likely to heat bedrooms than the North Island houses. This could explain why in Figure 39 the mean South Island heating index is not as high as that for the Central North Island. Only about 5% of HEEP houses heat bedrooms on a 24 hour schedule.

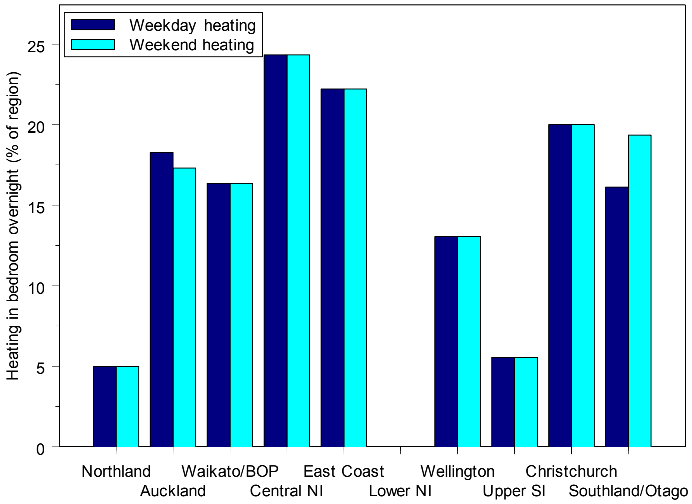

Figure 40: Bedroom overnight heating by region and weekday/weekend

Overall there is constant heating in the living rooms of approximately 10% of the HEEP houses. Figure 41 and Table 35 shows the majority of these houses are in Southland/Otago, the Central North Island and the East Coast of the North Island. These areas also have a higher proportion of houses with solid fuel burners than the other areas.

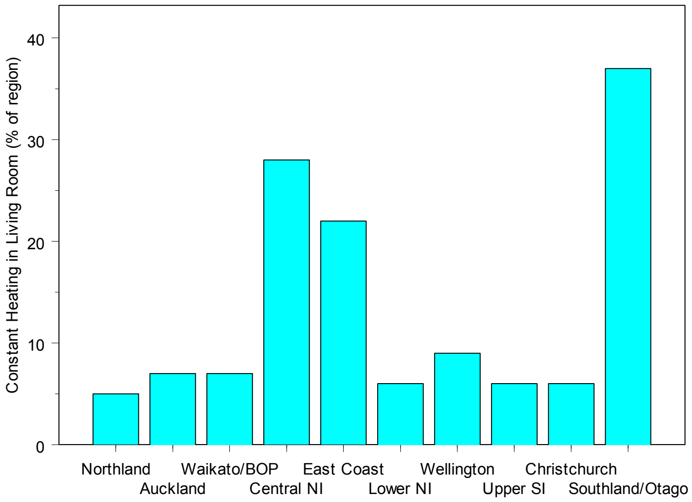

Figure 41: Living room 24 hour heating by region

Region	*No heating*	*Evening heating*	*Constant heating*	*Sample count*
Northland	13%	55%	5%	40
Auckland	14%	49%	7%	102
Waikato/BOP	4%	44%	7%	54
Central North Island	3% (1 house)	36%	28%	36
East Coast	0%	41%	22%	27
Lower North Island	0%	71%	6%	17
Wellington	0%	53%	9%	45
Upper South Island	6%	53%	6%	17
Christchurch	0%	40%	6%	35
Southland/Otago	16% (3 houses)	21%	37%	19

Table 35: Reported evening, all day and no heating by region

Table 36 provides statistics from the occupant self-reported heating schedules. The living room is the most common room to be heated and most often this is in the evening, with approximately 85% of occupants heating. Under half (45.5%) only heat their living room in the evening on weekdays and 37.2% in the weekends. Utility rooms are seldom heated, with 67.3% on weekdays and 69.2% of houses on weekends not heating utility rooms. Approximately 50% of the houses heat their bedrooms on weekdays, with slightly less heating their bedrooms in weekends. The most common time for heating bedrooms is in the evening (~20%) followed by overnight (~6%). Constant heating is done in ~10% in the living room and ~5% in the bedrooms and utility rooms.

Room	Living		Bedroom		Utility	
Weekday/Weekend	Weekday	Weekend	Weekday	Weekend	Weekday	Weekend
Morning	1.5%	1.8%	3.2%	2.6%	3.0%	2.5%
All day	0.7%	1.6%	0.3%	0.7%	0.7%	1.0%
Evening	45.5%	37.2%	21.8%	19.7%	11.4%	9.0%
Night	1.7%	1.8%	6.7%	6.5%	1.2%	1.3%
Morning/day	0.0%	0.0%	0.2%	0.0%	0.2%	0.3%
Morning/evening	13.9%	11.3%	6.0%	4.7%	4.0%	3.0%
Morning/night	1.0%	1.0%	0.2%	0.3%	0.0%	0.0%
Morning/day/evening	9.3%	12.3%	1.4%	2.3%	3.0%	4.2%
Morning/evening/night	0.3%	0.3%	0.0%	0.3%	0.7%	0.5%
Daytime/evening	5.0%	10.3%	1.0%	2.0%	2.5%	3.0%
Evening/night	3.2%	2.8%	4.0%	4.0%	1.0%	0.7%
Daytime/evening/night	0.5%	0.8%	0.0%	0.0%	0.3%	0.5%
24 hours	10.9%	10.8%	5.0%	4.7%	4.7%	4.8%
No heating	6.5%	8.0%	50.2%	52.2%	67.3%	69.2%
When is heating used (based on above data):						
Morning	37%	38%	16%	15%	16%	15%
Day	26%	36%	8%	10%	11%	14%
Evening	89%	86%	39%	38%	28%	26%
Overnight	18%	18%	16%	16%	8%	8%
No heating	7%	8%	50%	52%	67%	69%

Table 36: Percentage of houses on various heating schedules

7.4.1 Pre- and post-1978 houses

A minimum standard of insulation was introduced for all new houses from April 1978, and there is a clear difference in temperatures between pre- and post-1978 houses (see Section 7.8). It is unknown if this is due to just the insulation requirements or a combination of factors such as the occupants' behaviour. A cross-tabulation was prepared between the heating schedule and house age (pre- or post-1978), but no significant relationship was found (p-value 0.33). It would appear that occupants in the pre-1978 houses do not use different heating schedules to post-1978 houses. There is a reversal in the percent of houses that heat constantly and those that heat only in the morning, daytime and evening between pre- and post- 1978 houses, as seen in Table 37.

House age	*Constant heating*	*Morning, day and evening heating*
Pre-1978	13%	8%
Post-1978	8%	13%

Table 37: Pre- and post-1978 heating schedule

7.5 Reported heating seasons

This section looks at reported heating seasons from the occupants and the following section looks at the heating season as determined by the monitored data, with a discussion at the end comparing the results. Table 38 and Figure 42 give the number of houses reporting the given start or finish month. Note that the six households that heat year round are given a January start and December finish month. The majority of houses (72%) reported starting in April or May and finishing in September or October.

Month		Number start	Number end
1	January	6	
2	February		
3	March	18	
4	April	131	
5	May	131	1
6	June	58	1
7	July	14	8
8	August	3	51
9	September	1	142
10	October		116
11	November		32
12	December		9

Table 38: Reported heating season

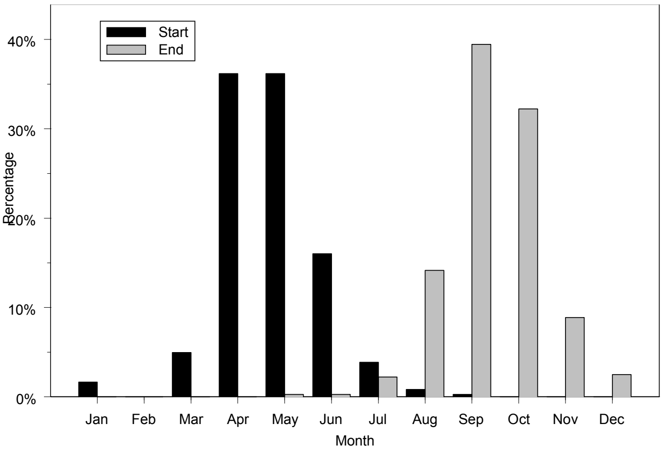

Figure 42: Reported heating season start and finish

Figure 43 (also based on survey data) gives the length of the reported heating season, with the number of houses in each band given in brackets on the y-axis. It shows that households that start heating early in the season also finish later in the season.

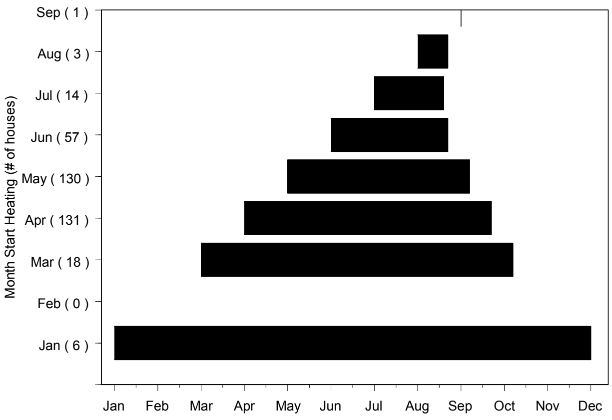

Figure 43: Length of reported heating season

Table 39 shows that the average starting and finishing heating seasons show statistically significant variations by region – households in cooler climates, on average, start heating earlier and finish heating later than those in warmer climates.

Month 1 in Table 39 is January through to month 12 which is December. The nearest month is given based on the rounded average.

On average, heating commences in late-April (4.7) and on average finishes in mid-September (9.4).

The starting month of the heating season is weakly related to the average winter evening living room temperatures, thus houses with warmer winter temperatures tend to start heating earlier in the season.

Region	Group	Start		Finish		Length	SD	Count
Kaikohe	Northland	6.4	June	8.4	August	2.0	0.4	8
Kamo West		5.4	May	9.1	September	3.7	0.5	10
Sherwood Rise		6.2	June	7.8	July	1.5	0.3	4
Orewa		5.7	May	9.2	September	3.5	0.9	6
North Shore	Auckland	4.9	April	9.5	September	4.5	0.4	15
Waitakere		5.2	May	9.2	September	4.0	0.4	13
Auckland		5.0	May	9.2	September	4.3	0.4	25
Manukau		5.3	May	9.1	September	3.7	0.4	18
Awhitu	Waikato/BOP	4.5	April	9.5	September	5.0	0.4	6
Parawai		4.7	April	9.6	September	4.9	0.6	9
Minden		4.7	April	9.3	September	4.6	0.9	10
Tauranga		5.8	May	8.6	August	2.8	0.9	5
Hamilton		5.2	May	9.8	September	4.6	0.3	12
Arapuni	Central NI	4.5	April	9.5	September	5.0	0.4	10
Western Heights		4.5	April	9.3	September	4.8	0.7	6
Ngakuru		4.4	April	9.4	September	5.0	0.4	8
Mangapapa	East Coast	4.2	April	8.7	August	4.4	0.2	9
Rangatira	Central NI	4.0	April	10.0	October	6.0	0.4	6
Wairoa	East Coast	4.8	April	9.2	September	4.4	0.3	9
Tamatea North	East Coast	4.8	April	8.8	August	4.0	0.6	8
Foxton Beach	Lower NI	4.4	April	9.7	September	5.2	1.0	9
Waikanae		5.2	May	9	September	3.8	0.2	6
Wellington	Wellington	4.7	April	9.5	September	4.7	0.3	22
Wai-iti	Upper SI	4.0	April	10.1	October	6.1	0.8	8
Seddon		4.0	April	8.9	August	4.9	0.3	7
Christchurch	Christchurch	4.5	April	9.3	September	4.8	0.3	31
Oamaru	Otago/Southland	3.8	March	9.9	September	6.1	1.1	8
Dunedin		3.8	March	10.2	October	6.4	0.7	12
Invercargill		4.0	April	10.2	October	6.2	0.2	6

Table 39: Average heating season by region (from north to south)

7.6 Monitored heating seasons

The months of heating were reported in the occupant survey, although some were unsure, reporting that it depends on the weather. This section looks at data from each individual house to determine when they start heating and how this relates to the outside temperature.

Accurate heating months could be determined for 302 houses, but these are spread around the country, averaging 80% of the houses in each monitored area. This sample is thus considered to be representative.

Heating times during the day were also reported by occupants in the initial survey, and this is the data that has been used for analysis in previous reports. However, closer examination of the temperature profiles and recorded heater use revealed that some houses use their heating appliances quite differently to manner they reported.

7.6.1 Determining when heating starts and concludes

Where heaters were monitored separately, heating times could be determined by examining the fuel usage data. 261 houses had separately monitored solid fuel, gas, LPG or fixed electric heating, although many of these also had portable electric heaters.

Portable electric heaters were monitored on a month-by-month basis in one-quarter of the houses. They were included in the total electricity consumption, but other large electricity uses had to be taken into consideration, and careful comparisons made between winter and summer use to determine the heater use. There is the potential for errors in this method, with some houses expected to have a slightly longer or shorter heating season than reported.

7.6.1.1 Solid fuel, gas, LPG and fixed electric heating

For the 261 houses with solid fuel, LPG, gas or fixed electric heaters which were recorded separately, determining the start and stop of the heating season could be determined from an examination of the fuel use patterns.

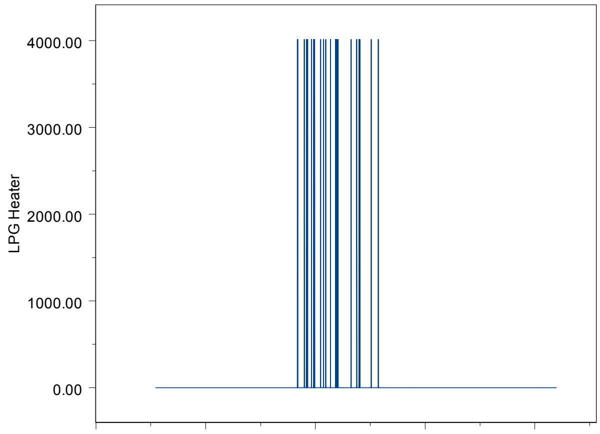

Figure 44: Example – LPG heater use

Figure 44 shows the usage of an LPG heater over a year (January to December). Zero use of the heater can be easily seen, as there is no energy consumed by the heater. The heating season determined from the LPG usage can then be compared with the season determined for the electric heater (see 7.6.1.2), as the occupants may have been using electric heating for a longer period than the LPG heater.

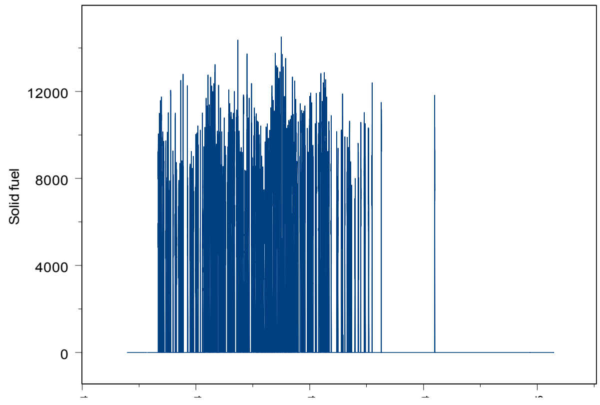

Figure 45: Example – solid fuel use

In the majority of houses there is a distinctive start and stop to the heating (e.g. Figure 44), although in some houses, there will be a period of heating followed by another period of no heating, as shown in Figure 45. Where the start and stop of heating is not clear, a decision was made based on the data for each house.

Thus for Figure 45, the end of the heating season was taken to be the end of the main heating period.

7.6.1.2 Electric heating

Electric and gas portable heaters were included in the total electricity and gas use of the house i.e. all electricity and gas use excluding water heating. This can cause problems when examining only the space heating energy use.

One method developed to determine heating use is to remove the hot water use from the total energy use, and then take an average of the electricity use for the warmer, immediately before winter, months of January, February and March. Examination of the daily energy use over the entire monitoring period highlights the increase. Most of this can be attributed to space heating, although in the majority of houses there is also an increase in lighting and cooking use in winter. The application of a confidence interval of 99% removes the effects of increased lighting and cooking, and in a small percentage of cases it may slightly reduce the apparent length of the heating season. Care has to be taken that houses that heat all year are recognised.

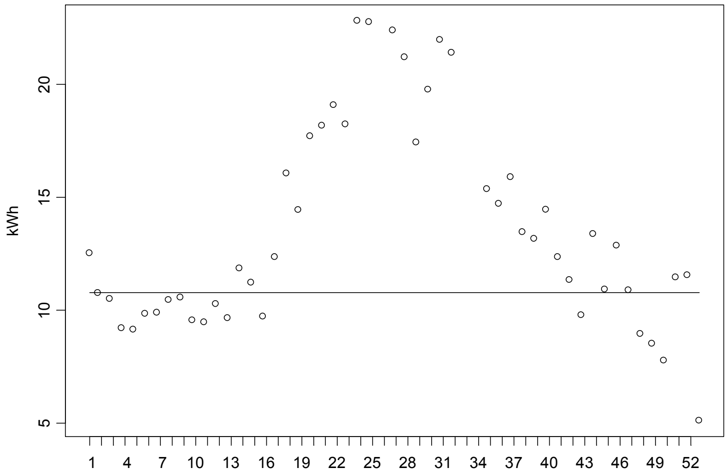

Figure 46: Non-hot water electricity use for one house

Figure 46 plots for a house the weekly total less DHW electricity. Energy use above the line (with a 99% confidence interval) is allocated as space heating.

7.6.2 Length of heating season

Figure 47 gives the number of houses with the given start or finish month while Figure 48 gives the length of the heating season. Houses were heated longer on average than the occupants reported. This may be due to occupants not realising how much they heat, or the monitored period could have been a more extreme winter than the occupants were expecting – the real reasons may differ from house to house, and are unknown.

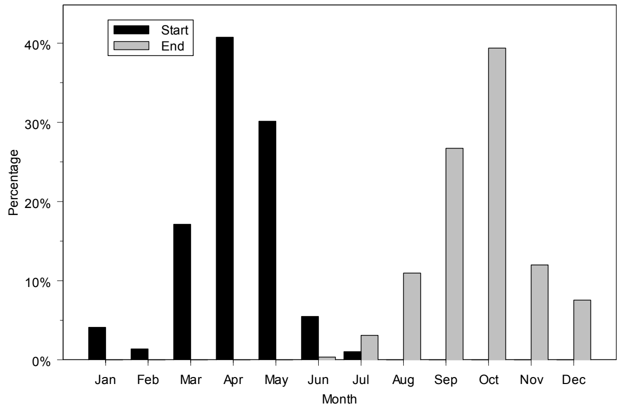

Figure 47: Months of heating – start and finish

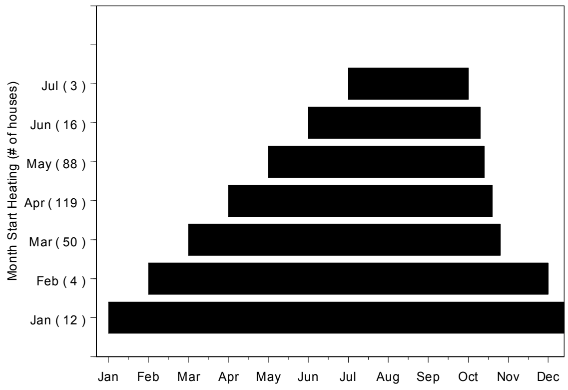

Figure 48: Length of heating season

Twelve houses in the sample heated for the whole year – approximately 4% of the total number of houses. In general these were in the cooler parts of the country (Central North Island and South Island).

Conversely, 10 houses in the sample did not appear to use heating at all – just over 3% of the total number of houses. In general these were in the warmer parts of the country (Auckland and north). These are not included in the above graphs or following tables.

Region	Start		Finish		Length	SD	Count
Northland	April	4.9	September	9.4	5.5	0.3	19
Auckland	April	4.5	September	9.2	5.7	0.2	79
Bay of Plenty	April	4.2	September	9.6	6.4	0.2	23
Waikato	March	3.8	October	10.2	7.4	0.3	41
Gisborne/Hawkes Bay	March	3.9	September	9.7	6.8	0.3	26
Taranaki/Manawatu-Wanganui	April	4.2	September	9.8	6.6	0.8	9
Wellington	April	4.2	September	9.4	6.1	0.2	28
Tasman/Nelson/Marlborough	March	3.6	September	9.9	7.3	0.6	13
Canterbury	March	3.9	September	9.5	6.6	0.3	27
Otago/Southland	March	3.3	October	10.8	8.6	0.5	27

Table 40: Heating start and end month by region

7.6.3 To what temperature do people heat?

The average monthly external temperature was calculated from NIWA National Climate Database and then used to determine the temperature at which each house started heating. Figure 49 shows the external temperature and the energy use for an example house. The time of the year when heating was occurring is outlined in red – which is also when the external temperature was coldest. This graph is smoothed by a seven day rolling average. Note the graph commences in October (month 10).

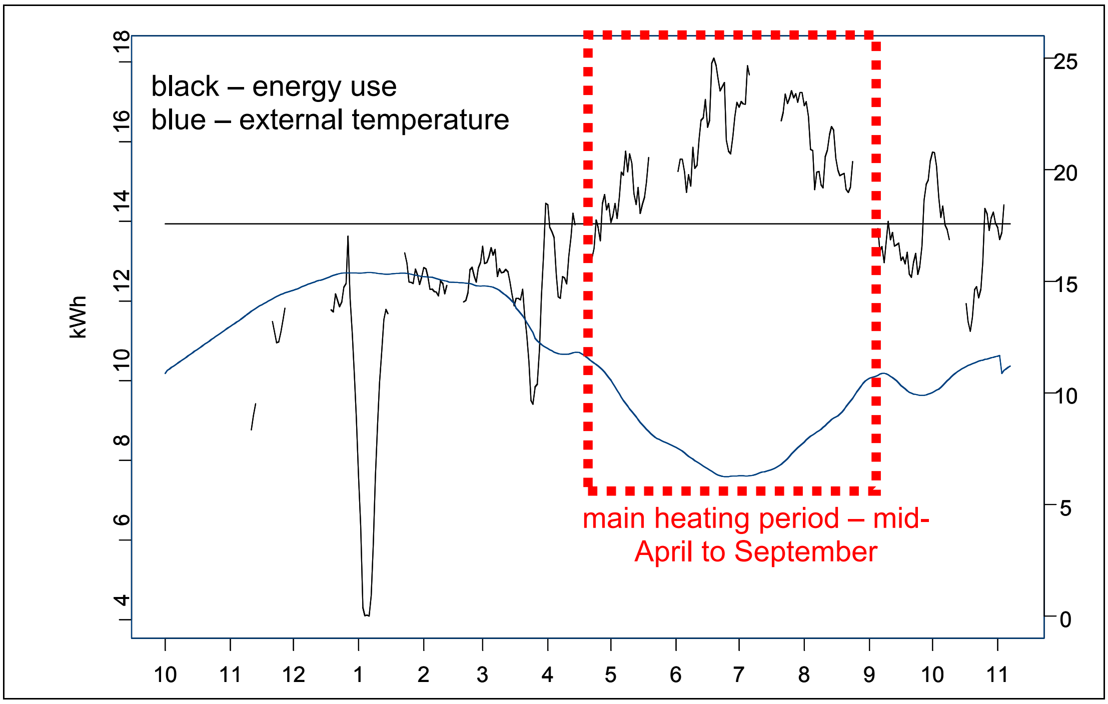

Figure 49: External temperature and energy use during heating season

As the external temperature dropped, the heating energy use increased in most houses – although there were still some that managed the winter without heating. There is no doubt that the further south one lives, the cooler the external temperature before heating is started. The average external temperature in summer for Invercargill is below the threshold for heating in Auckland! The solar gains in Invercargill would help increase the indoor temperatures. The temperature ranges are given in Figure 50 and Table 41 by region.

Regional Council	Average Temperature °C	Average Temperature SD	Start Temp. °C	End Temp. °C	Count
Northland	13.8	0.5	15.2	15.2	25
Auckland	12.7	0.2	15.1	14.7	81
Bay of Plenty	11.5	0.3	14.2	14.2	23
Waikato	10.6	0.2	13.1	14.5	39
Gisborne/Hawkes Bay	10.8	0.3	13.7	13.8	23
Taranaki/Manawatu-Wanganui	11.3	0.3	13.7	13.5	9
Wellington	9.9	0.2	13	12.4	29
Tasman/Nelson/Marlborough	9.6	0.3	12.6	13.2	11
Canterbury	9.1	0.2	12.3	11.7	27
Otago/Southland	9.0	0.2	11.7	13.5	27

Table 41: External temperatures over heating season

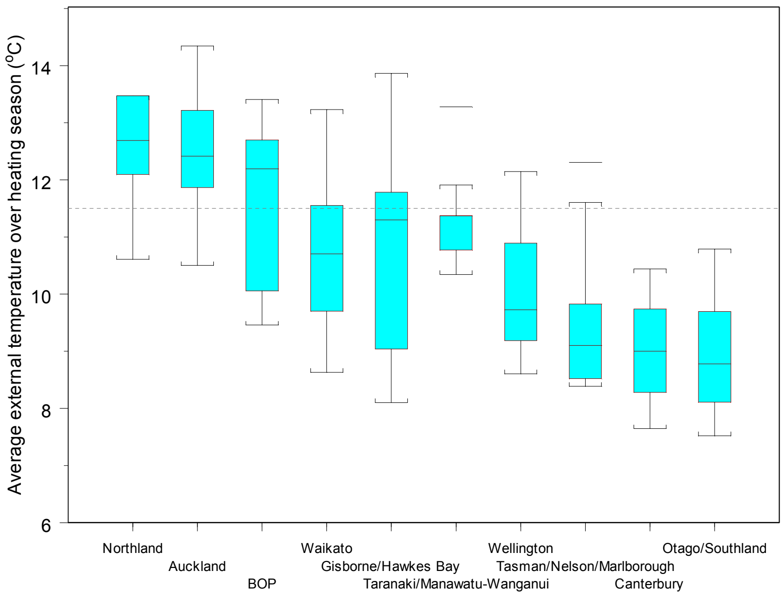

Figure 50: Average external temperature for heating season

There is a significant relationship between the region and the temperature houses start to heat or finish heating.

Heating does not necessarily occur during the coldest months. Figure 51 shows the heating-start external temperature is not necessarily the same as the heating-stop temperature. From the Waikato south, on average the last month of heating is warmer than the first month of heating.

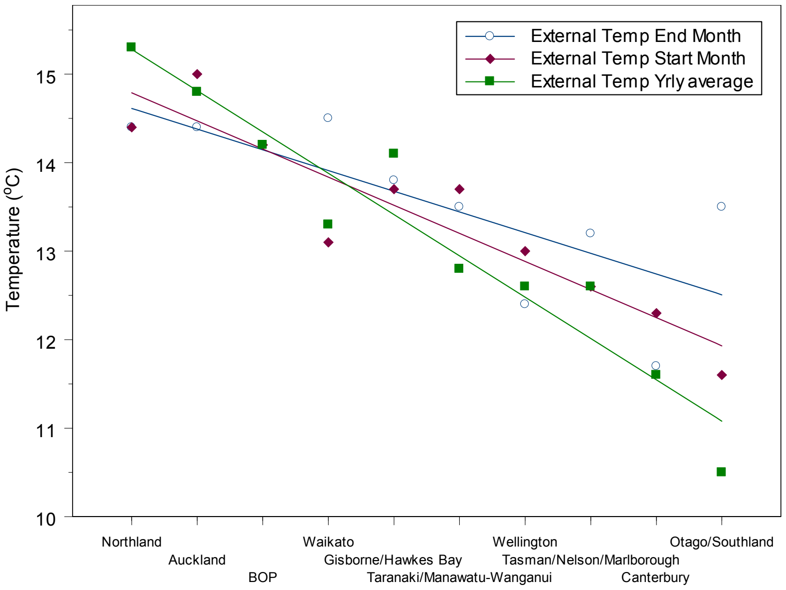

Figure 51: External temperatures of heating start and finish months

The yearly average external temperature used in Figure 51 is the average temperature compiled over several years. External temperatures for both the start and finish months are for the year that house was monitored.

7.6.4 Comparison between reported and monitored heating months

As part of the house survey, occupants were asked which months they heat their home. These reported months were used in the early analysis of heating months and summarised in the previous section.

When the pattern of heating is evaluated based on the monitored energy use, it appears that, overall, occupants heated for a longer period than reported. The reasons for this are not obvious – maybe the monitored year was a colder year than they were predicting, or possibly they heated more than they realised.

The difference between the reported and the measured months is statistically significant nationally, although not regionally.

The main differences occurred in houses that claimed to heat only for a short period of the year. Occupants who reported heating around five months upwards were found to heat for a period close to the months they reported. On average occupants heated for just over one (1.1) month longer than they reported.

7.6.5 Heater type and heater fuel

Heating type is an important factor in the achieved temperatures. Table 42 shows average winter evening living room temperature by heater type. Living rooms heated by open solid fuel fires are coolest, averaging 16°C (61°F), followed closely by portable electric heaters. Rooms heated by enclosed solid fuel burners are the warmest, averaging 18.8°C (66°F).

Heater type	Temperature °C	Std. error of mean °C	Sample count
Open solid fuel	16.0	0.6	11
Electric	16.9	0.3	83
LPG	17.0	0.2	54
Fixed electric	17.8	0.3	18
Heat pump	18.0	0.4	4
Gas	18.1	0.5	28
Gas central	18.3	0.6	8
Solid or liquid fuel central	18.5	0.7	2
Enclosed solid fuel	18.8	0.2	142

Table 42: Winter living room evening temperatures by heater type

Table 43 shows for each heating fuel type the percentage of time the average winter evening living room spends below 16°C, in the range of 16°C to 20°C, and above 20°C. The heating system may be unit heaters (for example a free-standing LPG heater) or whole-house central heating (for example natural gas ducted air central heating).

Heater fuel	<16°C (%)	Std. error of mean	16-20°C (%)	Std. error of mean	>20°C (%)	Std. error of mean	Sample count
LPG	34%	3%	53%	3%	13%	2%	54
Electricity	33%	3%	51%	2%	16%	2%	103
Natural gas	22%	5%	51%	4%	27%	5%	35
Solid fuel	23%	2%	41%	2%	36%	2%	151
All houses	28%		47%		25%		328
NA	34%	4%	46%	3%	19%	4%	39

Table 43: Living room winter evening temperature distribution

Table 43 shows that houses heated by solid fuel burners are the warmest and are warm for the longest time, with 77% of the time above 16°C. LPG and electrically heated houses are the coolest, being above 16°C only 66% of the time.

Although the costs of the different fuels may be relevant, the 'size' of the heater is likely to be of greater importance. Solid fuel burners produce large amounts of heat output, although it is difficult to control. Typically, solid fuel burner heat output ranges from 4 kW to 25 kW, but this is in ideal conditions. A one-bar electric heater is 1 kW. Normally the HEEP houses were found to run their solid fuel burners between 3-5 kW. This could explain the high numbers of solid fuel houses spending time above 20°C.

The highest living room winter temperature measured in a HEEP house was 42°C – which is warmer than any temperature reached during summer – and this house was heated by a solid fuel burner.

Just under one in five houses (18.5%) reached maximum temperatures above 30°C in winter (81% of these had enclosed solid fuel burners). Almost half the houses (44.5%) reached maximum winter evening temperatures above 25°C.

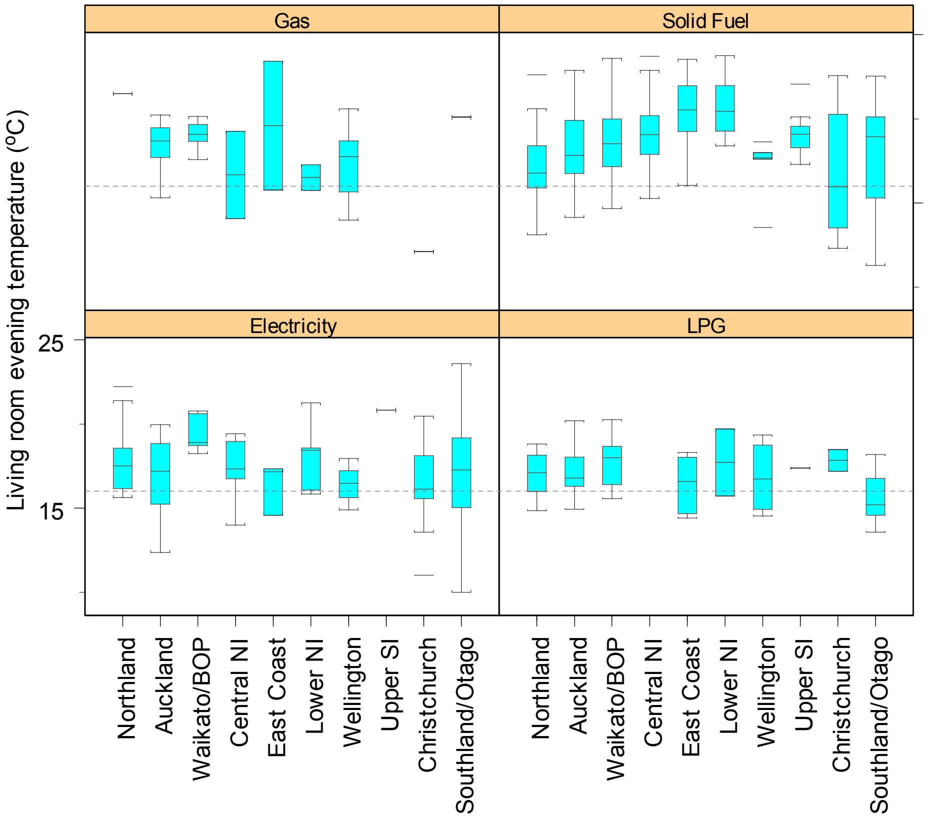

Figure 52: Living room evening temperature by location and most used heating fuel

7.7 House age

There is a strong relationship between house age and the winter living room evening temperature. Figure 53 shows that older houses tend to be colder. There is an average rate of fall 0.20 ±0.05°C per decade, with a high statistical significance (p-value 0.000045). This result is without considering any retrofitted thermal insulation, the heating fuel, region, or occupants' heating patterns.

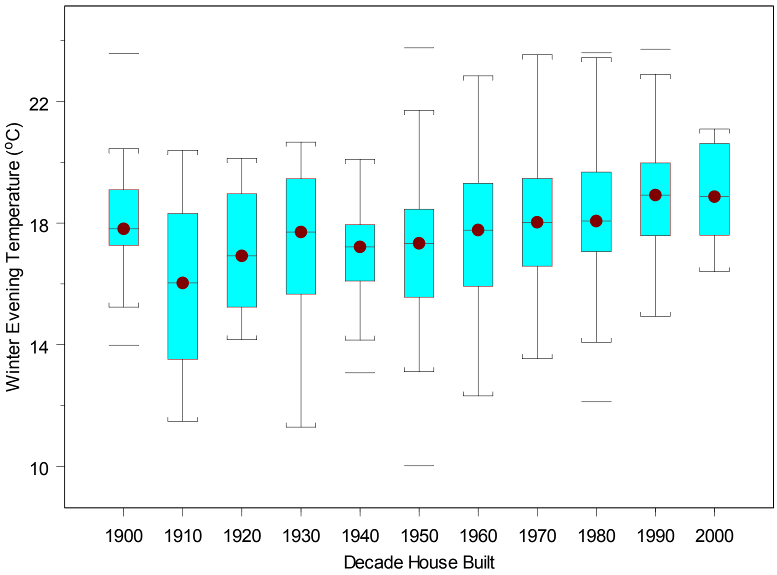

Figure 53: Winter evening living room temperatures by year built

The housing stock in the Otago/Southland area is oldest, with only 11% of houses being post-1978. Over all of New Zealand, the average Regional Council will have 25% of its houses built post-1978. The older housing stock, with climate, would help explain the low winter temperatures for some of the houses in Otago/Southland.

7.8 Thermal insulation

Houses built after 1 April 1978 are required to include a minimum level of insulation, but the retrofitting of thermal insulation was not required in older houses. As seen in Table 44 there is a 1.0°C difference in living room evening temperatures between pre- and post-1978 houses. Table 44 also shows the same pattern can for bedrooms.

House age group	Average winter evening living room temp (°C)	Std. error of mean (°C)	Sample count	Bedroom overnight temp (°C)	Std. error of mean (°C)	Sample count
Pre-1978	17.6	0.1	265	13.2	0.1	243
Post-1978	18.6	0.2	99	14.5	0.2	95

Table 44: Winter temperatures by insulation level

This pattern continues regionally (Table 45 and Figure 54) with all post-1978 houses being warmer than pre-1978 houses. In Christchurch and Wellington there does look to be little difference; this is possibly because of the heater type used in some of these houses. There is a disproportionate number of gas centrally heated houses in the pre-1978 Wellington houses, resulting in warmer temperatures. In Christchurch there is a cold post-1978 gas heated house, and nine enclosed solid fuel heated houses that are pre-1978, with only one post-1978. It is possible that the differences in heating appliances between the pre- and post-1978 groups are overriding the tendency for post-1978 houses to be warmer. There are no post-1978 houses in the East Coast region sample.

Regional group	House age	Living room °C	Standard deviation	Subsample count	Total count
Northland	Pre-1978	17.1	0.4	27	36
	Post-1978	18.8	0.5	9	
Auckland	Pre-1978	17.1	0.3	62	89
	Post-1978	18.2	0.3	27	
Waikato/BOP	Pre-1978	18.3	0.3	29	54
	Post-1978	19.1	0.4	25	
Central NI	Pre-1978	18.2	0.4	23	36
	Post-1978	19.6	0.7	13	
East Coast	Pre-1978	18.8	0.5	27	27
Lower NI	Pre-1978	18.8	0.8	11	16
	Post-1978	18.8	0.8	5	
Wellington	Pre-1978	16.8	0.4	26	30
	Post-1978	16.7	0.8	4	
Upper SI	Pre-1978	18.7	0.3	13	18
	Post-1978	19.4	0.8	5	
Christchurch	Pre-1978	16.9	0.6	21	29
	Post-1978	16.8	0.9	8	
Southland/Otago	Pre-1978	17.1	0.7	26	29
	Post-1978	20.1	1.0	3	

Table 45: Regional living room temperatures by insulation requirements

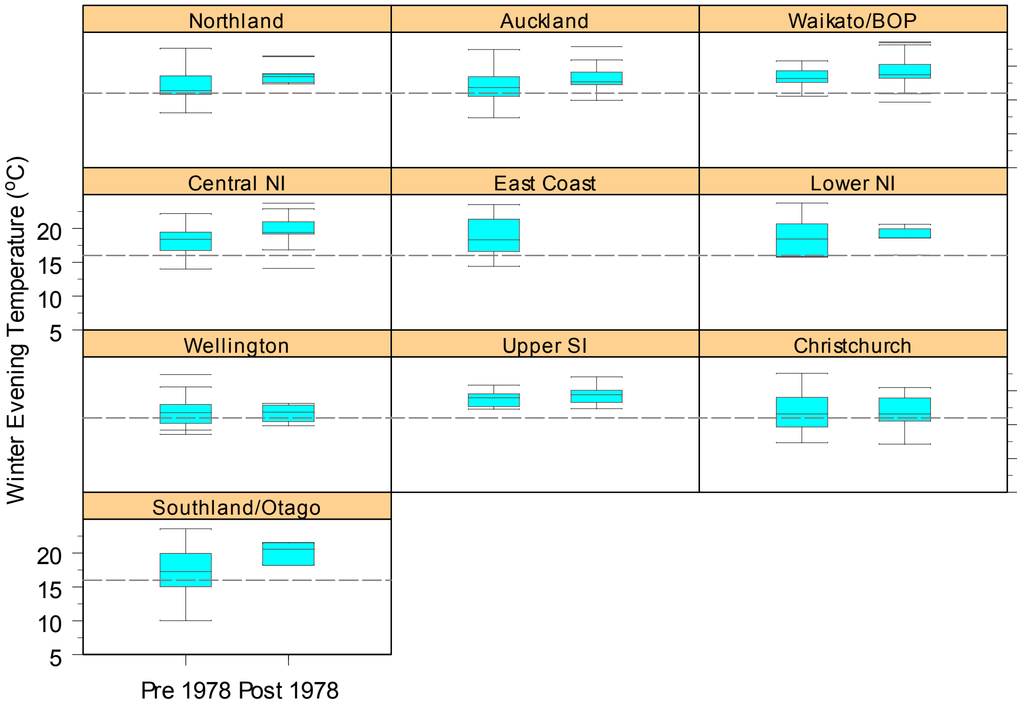

Figure 54: Regional living room temperature differences by insulation requirements

The same pattern occurs with overnight bedroom temperatures. Even though the lack of bedroom heating leads to lower average temperatures, post-1978 houses are warmer than pre-1978 houses. Bedroom temperatures were not monitored for all the Wellington houses, so there is not enough information to make a good comparison in this location.

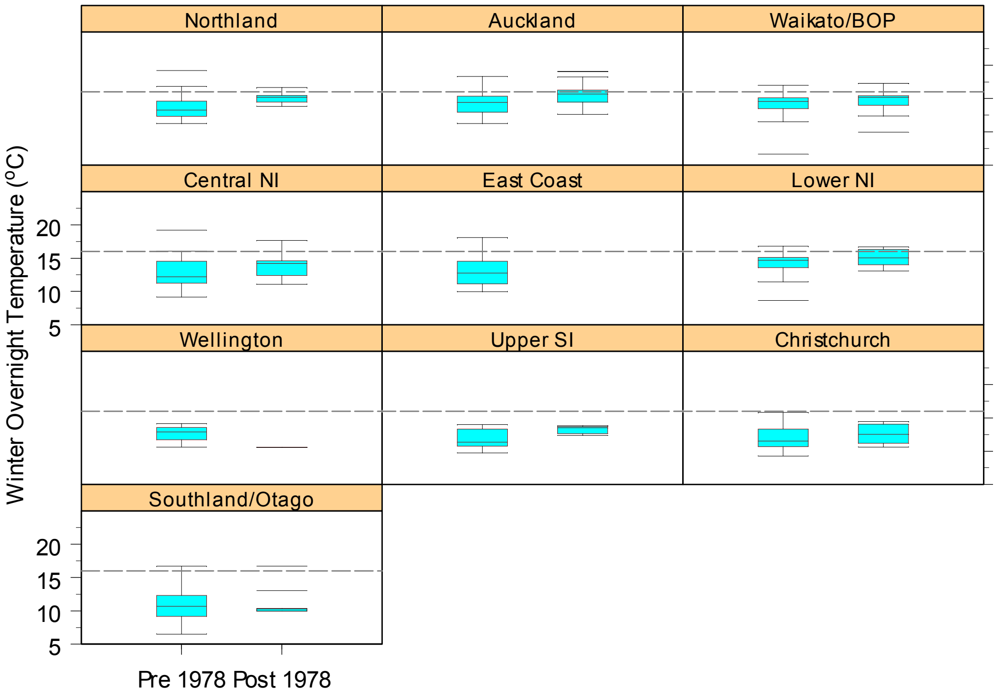

Figure 55: Regional bedroom temperature differences by insulation requirements

7.9 Temperature stratification

Winter temperature stratification in the living room was examined. The loggers were placed at 1.6m to 2.2m and 0.2m to 1m from the floor in the living room. Because of the furniture and the set up of the room the heights of these two sensors could vary a lot. There was also variation in how the loggers were situated; for example, some loggers may have been protected from radiant heat behind pictures, and others protected from draughts in a bookcase. The temperature loggers are known to measure what a person would feel if they were in the same place as the logger. Some of the early monitoring only had one logger in the living room and some houses do not have complete winter data. If more than 40% of the winter data was missing from either the high or low logger the house was excluded from the sample. The greatest mean temperature difference in any one house between the upper and lower loggers is nearly 10°C (Figure 56).

In most houses it was found during winter that the upper logger was recording a higher temperature than the lower logger (houses with under floor heating were an exception to this). This difference in temperature was found be influenced by region, by heating source and the overall room temperature. Using these three variables in a lineal model explains 56% of the variation (p-value 0.000)

House age is significant but only explains a small amount of the variation; it is most likely significant because of the decreased heat losses in new houses through increased insulation. With heating being so important to the stratification this will reduce the importance of the house age.

Regional Council	Temperature difference (^{o}C)	S.E.	Count of Houses
Northland	1.4	0.3	30
Auckland	1.5	0.1	101
BOP	2.4	0.4	25
Waikato	2.3	0.2	46
Gisborne/Hawkes Bay	4.0	0.4	23
Taranaki/Manawatu-Wanganui	2.7	0.5	10
Wellington	1.8	0.8	9
Tasman/Nelson/Marlborough	4.0	0.4	16
Canterbury	2.5	0.4	28
Otago/Southland	2.8	0.4	27

Table 46: Temperature difference between upper & lower logger by regional council

Table 46 shows the temperature difference between the lower and upper sensor by regional council. The differences between region look to relate to the amount of heating occurring in the area as well as the type of heater predominately used. The difference between regions is significant.

Most used heater	Temperature difference (^{o}C)	S.E.	Count of Houses
Piped gas (flued) non central	3.6	0.8	9
Enclosed wood/coal burner	3.4	0.2	121
Electric night-store	2.1	0.5	9
Piped gas (un-flued) non central	2.1	0.5	10
LPG heater	1.6	0.2	44
Open fire	1.6	0.4	10
Electric panel heater	1.5	2	2
Portable convection heater	1.5	0.2	33
Portable fan heater	1.5	0.3	21
Gas central heating	1.3	0.1	3
Portable electric radiator	1.3	0.2	15
Gas under-floor heating	1.1	NA	1
Heat pump	0.8	0.6	2
Electric radiators	0.6	0.8	2
Dehumidifier (with heater)	0.3	NA	1
Wall fan heater	0.3	NA	1
Solid or liquid fuel fired central heating	0.2	NA	1
Electric under-floor	-1.4	1	2

Table 47: Most used heater type and temperature difference

Table 47 shows the difference in temperature between the upper and lower temperature sensor grouped by the most used heater reported by the occupant. The heater types that are shaded have high standard error compared to the temperature difference and the results should be looked at with care. Gas central heating only has a small sample count (three houses) but has a low standard error and is significant; however, given the small sample size and the houses all being in the upper north island there may be large variation in temperature if used elsewhere or the heater is operated differently. It should be noted there is no statistical difference between the three portable electric heaters.

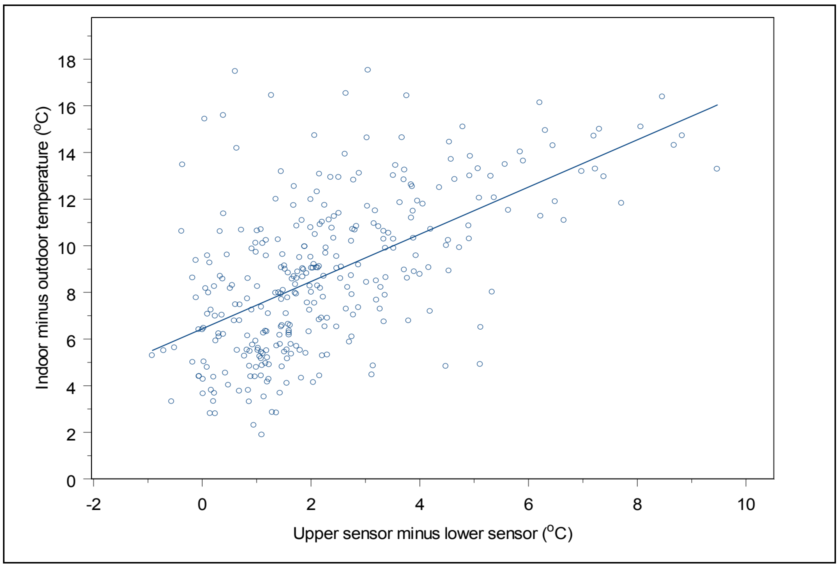

Figure 56: Relationship between temperature difference from the high and low loggers and the difference between outside and inside (linear fit line)

Houses that heat intensively (have a larger temperature difference between inside and outside) have greater temperature stratification inside. The difference between the inside and outside temperature explains 32% of the variation between the lower and upper sensor in the living room.

$$LivingRoomDifference = -0.5667 + \Delta T * 0.3249$$

Equation 12: Living room temperature stratification

Where:

LivingRoomDifference	The difference between the two temperature sensors in the living room
ΔT	The temperature difference between inside and outside

7.10 Winter temperature discussion

New Zealand houses have lower temperatures in winter than found in other countries with similar temperate climates. The average winter evening living room temperature is 17.9°C, while the mean range is from 10°C to 23.8°C.

About 5% of New Zealand houses have central heating systems. In the other houses, the tendency is to zone heat, with the most common room heated being the living room and the most common time of heating being the winter evening.

Solid fuel burners heat the houses well but with little control – they can produce high room temperatures. Houses heated by open fires (solid fuel) and portable electric heaters are the coolest, with mean winter living room evening temperatures of 16°C and 16.9°C respectively. Houses heated by enclosed solid fuel burners are the warmest, with a mean winter living room evening temperature of 18.8°C.

Newer houses are warmer during winter than older houses; reasons for this may include higher levels of thermal insulation and increased airtightness.

Comparing pre- and post-1978 houses, the winter evening living room temperatures in the newer houses are on average 1°C warmer – 1978 is when the first compulsory regulations were introduced for insulation in houses. This temperature difference increases to 1.3°C in the bedrooms, which seldom have formal heating appliances (the main heating sources are human bodies, TVs, clock radios and pets).

8. SUMMER TEMPERATURES

Few HEEP houses were heated or cooled during the summer months (December, January and February). This is partly because only 4% have air-conditioners or reverse cycle heat pumps. 3% do heat throughout the whole year, although these tend to be in the cooler, southern, parts of the country.

Figure 57 shows the distribution of living room mean daytime (9 am to 5 pm) temperatures over the summer months for all HEEP houses. Eighty-five percent have a mean living daytime temperature between 20°C and 25°C, while fewer than 1% are over 25°C and just over 14% are under 20°C. HEEP analysis found the average mean daytime living room summer temperature to be 21.8°C, the maximum mean temperature 25.9°C, and the lowest mean temperature 16.3°C.

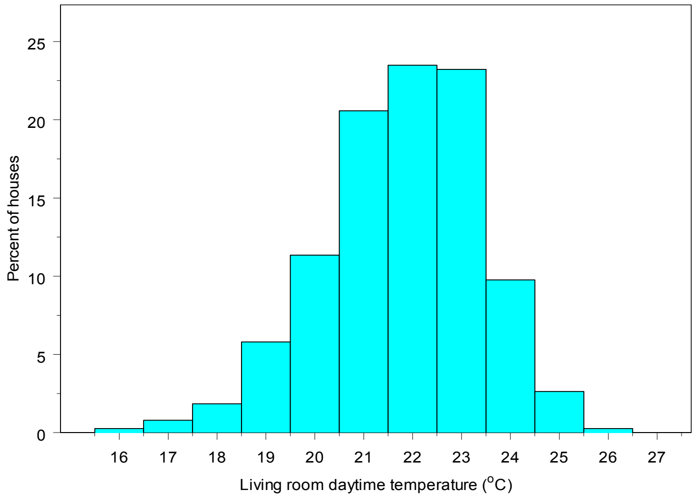

Figure 57: Mean living room temperatures

Figure 58 shows the distribution of the proportion of time between 9 am and 5 pm that living room temperatures are under 20°C, between 20°C and 25°C, and over 25°C.

Nearly four out of five houses (78%) spend more than half the day between 20°C and 25°C. Of the other houses (22%), over half (13%) spend more than half the day below 20°C. However, 1% spend over 50% (four hours per day) of the summer daytime above 25°C. This 1% can be considered to be at uncomfortably high temperatures for over half the day.

Over all the houses, the majority (80%) spend less than 25% of the summer daytime (two hours per day) at temperatures over 25°C. Most houses are between 20°C and 25°C for most of the time. As we have not collected data on the occupants' opinion of comfort or other climatic factors (such as air changes per hour, humidity and clothing levels) it is not possible to definitively conclude that these are comfortable temperatures. However, these would be considered comfortable based on overseas definitions.

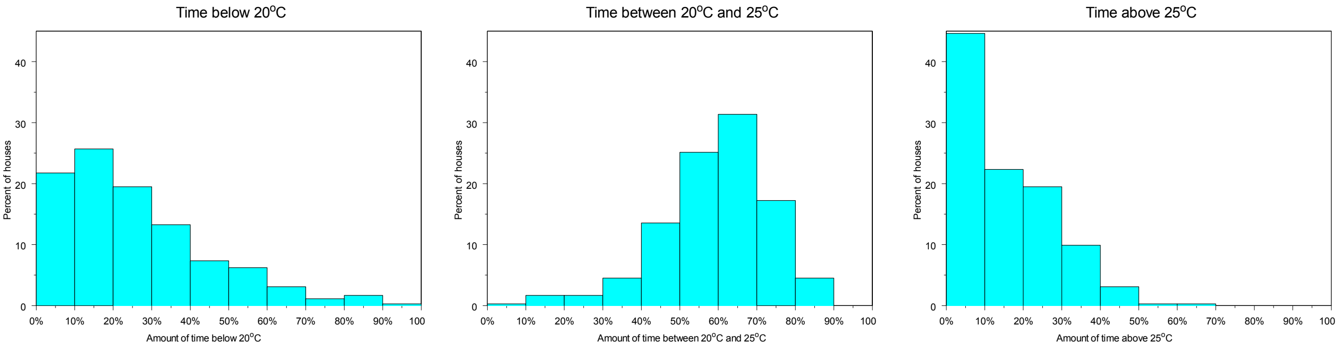

Figure 58: Time spent at given temperature ranges

Table 48 gives the mean temperatures for four different periods of the day for the ambient external temperature, the bedroom and the living room. Table 48 shows the bedroom is always slightly cooler than the living room. Analysis of the HEEP houses has found that they have randomly oriented windows (on average about 25% of the total glazing is in each compass direction), with living rooms also being randomly oriented. This may explain the small temperature difference between living rooms and bedrooms in summer when little or no heating is applied, as neither can be guaranteed to benefit from the sun.

The periods when the bedroom temperature is closest to the living room temperature are the night (midnight to 7 am) and the morning (7 am to 9 am). These are times when the bedroom is likely to be occupied and therefore have internal heat gains (from TVs, clock radios, pets and human bodies). The bedroom also has less of a temperature decrease from evening to night than the living room, again likely to be caused by the internal gains.

The moderating effect of the house can be seen in the 3.9°C mean temperature range for the living room (from 19.2°C to 23.1°C), which is not as large as the 5.6°C ambient temperature range (from 14.5°C to 20.1°C). Houses with high levels of thermal mass (which will have a stabilising affect on temperatures; for example, concrete or double wall brick – see Donn and Thomas 2001) would be expected to have a lower temperature range. However, this could not be confirmed as there are only two such houses in the sample. Most New Zealand houses are timber-framed with an external veneer and are considered to be low thermal mass.

	Mean temperatures for all houses			
	Morning 7 am to 9 am	**Day 9 am to 5 pm**	**Evening 5 pm to 11 pm**	**Night Midnight to 7 am**
Living room (°C)	19.2	21.8	23.1	20.3
Bedroom (°C)	19.1	21.2	22.6	20.1
Ambient (°C)	15.8	20.1	17.9	14.5

Table 48: Mean temperature during time periods

This distribution of living room and bedroom temperatures and the shift between morning and daytime is shown in Figure 59. The living room temperature distributions are shown in the two graphs on the left and the bedroom temperature distributions are shown in the two graphs on the right. The top two graphs show the distribution of morning temperatures and the lower two show daytime temperatures.

The range of temperatures for both the bedroom and the living room during the morning is approximately 14°C to 24°C, with a mean of 19°C. During the daytime the temperatures range from 16°C to 26°C with means of 21°C for both the bedroom and the living room. This is an increase in both the range and the mean of 2°C from the morning (shown by the dotted line and arrow on Figure 59).

The shapes of both the morning temperature distribution histograms for the living room and bedroom are similar; with the bedroom mean 19.1°C and the living room 19.2°C.

The temperature range for bedrooms is slightly lower than for living rooms, but the overall shape is similar, with the day means of 21.1°C for the bedroom and 21.8°C for the living room.

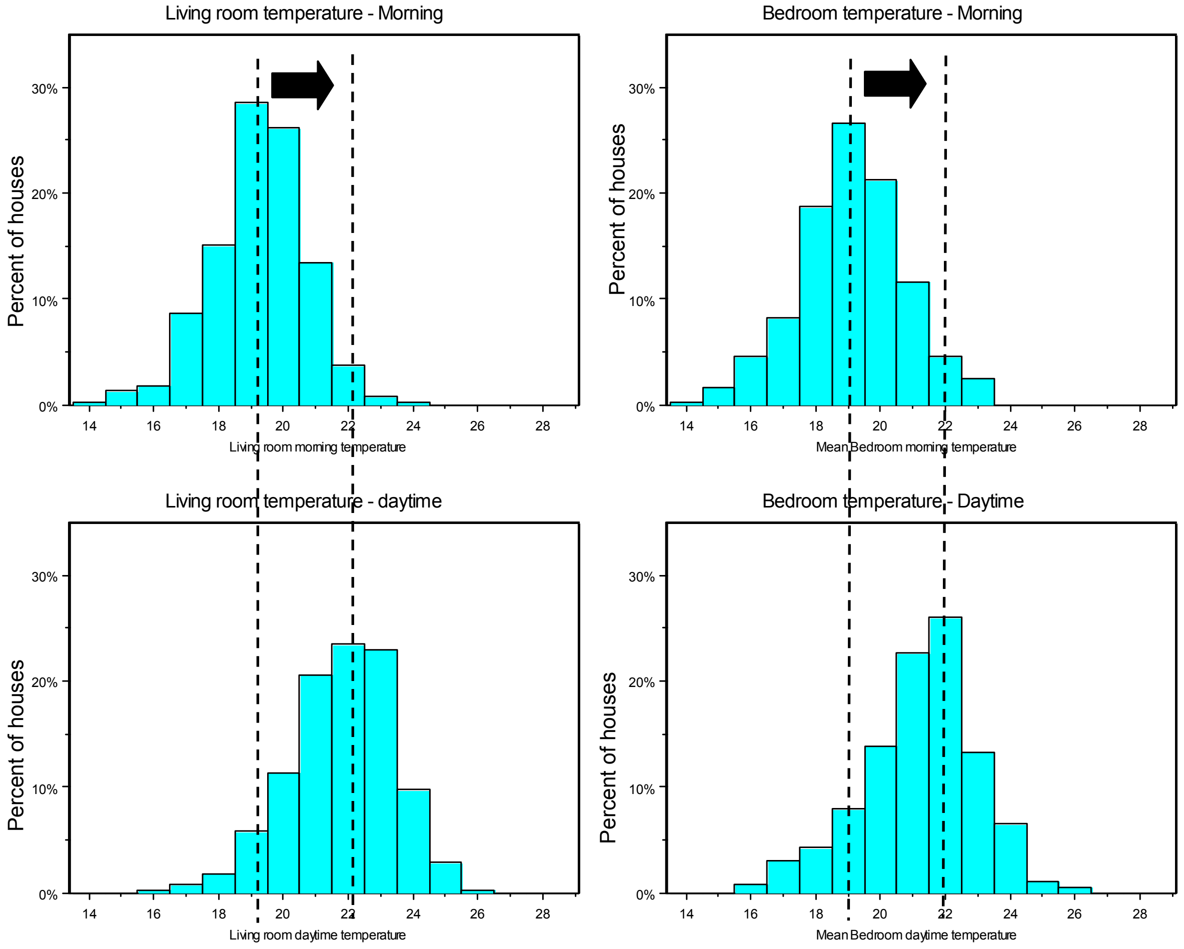

Figure 59: Living and bedroom temperature distribution for morning and day

8.1 Maximum temperatures

The time of day the maximum living room temperature is reached and the living room maximum temperature distribution are plotted in Figure 60 and Figure 61.

The temperatures reported here are the maximums reached over the three months of summer. Data from 14 houses (3.5%) was removed from the analysed sample due to the maximum temperature being recorded when the house was being heated. In the other houses, there is no obvious reason why living rooms should reach such high temperatures during the summer.

On average, the maximum temperature in the living room is reached at 5.40 pm, although the time of day varies by region (as seen in Figure 60). Auckland (in the north) has a mean time of maximum temperature of just after 5 pm and the Otago/Southland region has a mean time of 6.40 pm. The sunset at the start of January varies from 7.43 pm in Auckland (36° 52' S 174° 45' E) to 8.42 pm in Invercargill (46° 25' S 168° 21' E). Although there are still outliers, the range of times is closer the further south the region.

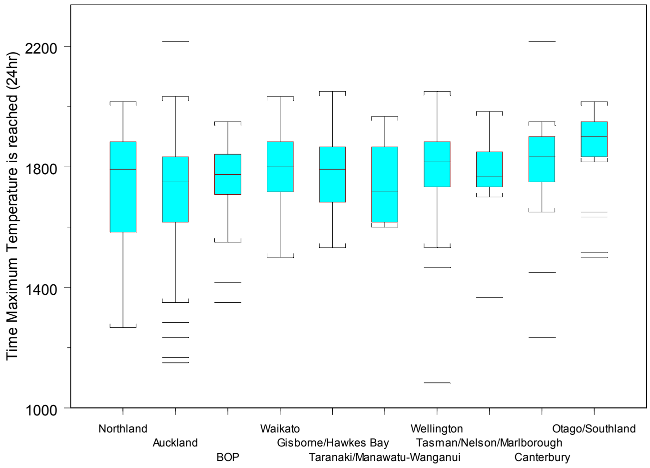

Figure 60: Time of maximum living room temperature by Regional Council

The distribution of the maximum summer temperatures is plotted in Figure 61 by region. This variation is not a simple north to south variation, but clearly depends on other reasons which may include:

- **regional geography** – both Wellington and Dunedin are hilly with some houses getting little or no direct sun inside the house. Large variations in temperatures can be seen in these regions
- **sun angles, sunrise and sunset times** – the sun sets later in the far south than in the north and rises earlier in the far north because of it being further east
- **house variations** – age (proportion of older/newer houses), window sizes and orientation, construction and shading
- **sunshine hours** – these vary throughout the country with the upper South Island (Tasman/Nelson/Marlborough) having the highest sunshine hours, followed by the east coast of the North Island (East Coast/Hawkes Bay). Of the HEEP locations, Dunedin has the lowest sunshine hours with Invercargill next – both of these locations are in the Otago/Southland region (NIWA 2006).

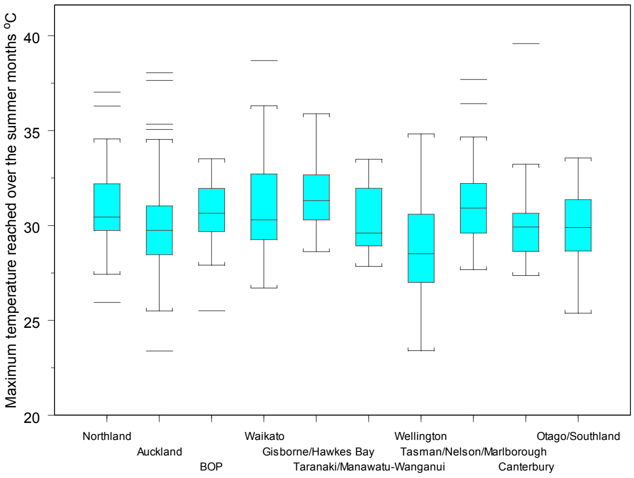

Figure 61: Maximum living room temperature by Regional Council

8.2 Influences on indoor temperatures

The main drivers of summer living room daytime temperature have been found to be the climate and the house age.

8.2.1 Climate/regional differences

The differences in mean daytime living room temperature by Regional Council can be seen in Figure 62 (the black squares show the mean ambient daytime temperature for the region). It is clear that the warmer the climate, the warmer the living room temperature. For example, the median living room daytime temperature in Northland is 22.5°C compared with 19.5°C in Otago/Southland (3°C difference).

Figure 62 shows the mean daytime (9 am to 5 pm) temperatures over the summer months for HEEP houses. The houses are grouped by Regional Council or groups of these Councils when there are small numbers of monitored houses in their regions. The graph is ordered from the north to the south (left to right); this shows how the warmer climate in the north affects the interior temperature compared with the colder southern climate.

Figure 62 shows the mean daytime summer ambient temperatures are similar in the southern-most region of the North Island (Wellington) and the northern-most regions in the South Island (Tasman/Nelson/Marlborough). This is at least in part a function of geography – both Nelson and Wellington are at 41°S.

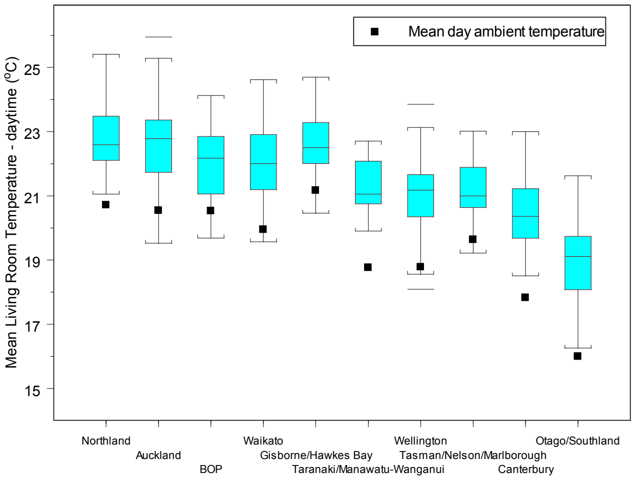

Figure 62: Mean living room daytime temperatures by Regional Council

The means of the daytime living room mean temperatures shown in Figure 62 range from about 20°C to about 23°C, apart from Otago/Southland with a mean of 16°C.

Analysis of the data shows that for each increase of 1°C for the average external temperature,[12] the mean house temperature increases by 0.81°C.

There is a 4.5°C difference between houses in Kaikohe (18.8°C mean external temperature) and houses in Invercargill (13.4°C mean external temperature) for summer daytime temperatures. Using climate alone this accounts for 68% of the variance ($r^2 = 0.68$, p-value = 0.0000).

8.2.2 House age

Newer houses are warmer than older ones (as seen in Figure 63). This difference is statistically significant (p-value 0.0000). Please note the 'Decade house built' is the reported decade of original construction, and that many of the older houses have been significantly modified.

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[12] Average external temperatures were calculated using NIWA CLIDB temperatures for the year the house was monitored.

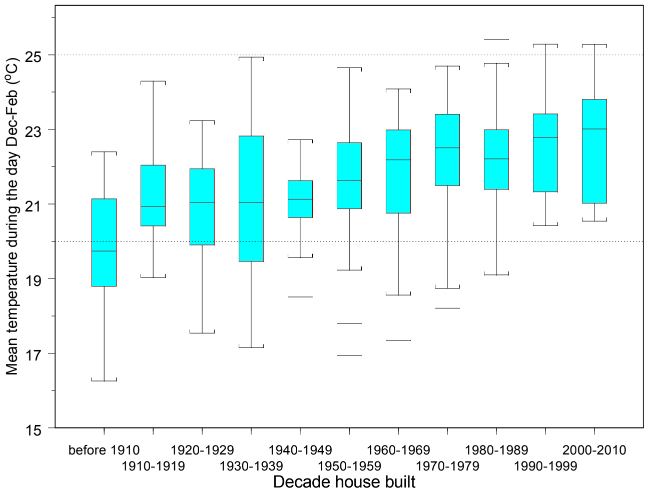

Figure 63: Summer temperatures by house age

The mean summer living room temperatures show a trend of increasing by 0.25°C per decade. This gives a difference of 2.5°C between houses built at the beginning and the end of the 20th century.

The dotted lines in Figure 63 are at 20°C and 25°C. Apart from the pre-1910 houses, the mean temperatures for all house ages are within this range. Houses built from 1990 onwards all have a mean daytime living room summer temperature of above 20°C, but the average temperature in this group is close to 23°C with extreme means above 25°C.

Examination of the difference between the living room temperature during the day and the ambient temperature found that as houses become newer, there is an increase in the inside-to-outside temperature difference of 0.22°C per decade. This is not unexpected as newer houses are better insulated. There is also a climatic driver in this temperature difference, but together the two only account for 11% of the variance ($r^2 = 0.11$, p-value = 0.0000).

One issue not explored here, but of concern, is the possible impact of higher summer temperatures because of either climate variability or climate change. As newer houses tend already to be warmer than older ones, their adaptation mechanisms to increased temperatures are potentially more problematic. Air-conditioners are becoming more and more popular, with one supplier reporting increases in sales of up to 35% per year (Ninness 2006). If they are used to reduce high summer temperatures, this will have undesired impacts on the electricity system.

8.3 Model of summer living room temperatures

The analysis was used to develop a simple model of summer temperatures. Equation 13 links the average external temperature for the summer months and the house age to model the expected summer daytime mean temperatures. Linear modelling found that these two variables account for (r^2 = 0.69) of the summer temperature variations (p-value = 0.0000). This equation is for the mean temperature over December, January and February for between 9 am and 5 pm.

$$SummerLivingRoomTemp. = -12.62 + YearBuilt \times 0.009 - AveExtTemp \times 0.76$$

Equation 13: Summer Living Room Temperatures

Where:

YearBuilt = year the house was built; for example, 1987

AveExtTemp = average external temperature for the months of December, January and February for the year the house was monitored.

Separate testing has found the house age and climate are independent.

Using these two variables (house age and external mean temperature) for other times of the day (for example, morning, evening and night) explain 60-69% of the variation, and explain 74% of the variation for a 24-hour mean temperature.

The house age without the average external temperature explains 14% of the variation in daytime living room temperatures.

8.4 Why are new houses warmer?

HEEP analysis has already shown that newer houses are warmer in both winter (Isaacs et al 2004) and summer. There are several reasons that could be causing this, e.g:

- **improved thermal performance** – since 1978 new houses are insulated
- **airtightness** – newer houses are less 'leaky'
- **increased glazing area** – a possible trend to increased use of glass
- **larger floor area** – permit trends are showing an increasing floor area
- possibly **better orientation of windows** for passive solar heating – although no clear indication of this can be found in the HEEP sample
- **lower ceiling heights** leading to lower room volumes
- **reduced or no eaves** – because of architectural trends
- **higher income –** of the occupants
- **northward shift** – newer houses more likely to be built in a warmer climate.

Using the HEEP sample, some of these options were explored to examine their impact on summer temperatures.

8.4.1 Thermal insulation

The thermal performance of house components (roof, wall, floor, windows) was not measured. It can, however, be assumed that post-1978 houses are likely to have a higher thermal performance than pre-1978 houses as houses built from 1978 onwards were required to have insulation at construction. The difference between pre- and post-1978 houses is significant (p-value = 0.0004) for the summer day temperatures. Although only 5% of the variation in the temperatures is explained from this, when including climate, 50% of the variation (p = 0.000) in daytime living room temperatures is explained. This is less than the 69% explained by house age and climate, suggesting there is more than just the difference in the levels of thermal insulation in pre- and post-1978 houses that affect the summer living room daytime temperatures.

8.4.2 Airtightness

A rating of each house's airtightness was recorded during the HEEP occupant survey. Four choices were provided, ranging from 'airtight' to 'draughty'. As this is a self-reported rating the accuracy is unknown, as is the consistency between houses.

The reported airtightness is plotted against mean living room daytime temperature in Figure 64. This shows that as airtightness increases, the mean living room daytime temperature also increases. However, when the outside temperature is considered, it overwhelms the influence of the reported airtightness. This may be because of the ability of occupants to easily alter the ventilation rate by opening or closing windows and doors. As there are many influences on door and window opening, it has proved impossible to predict the air change rate for any given house.

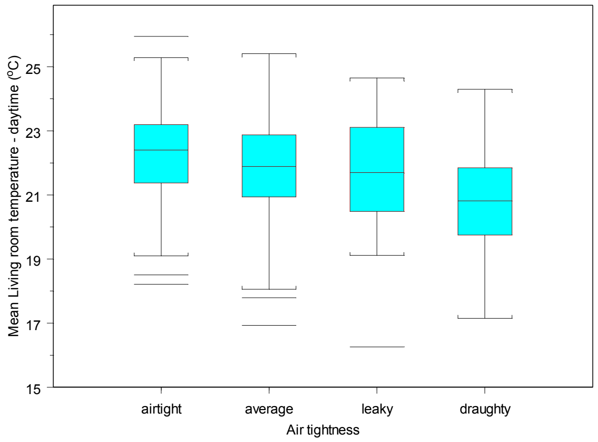

Figure 64: Mean living room temperature by airtightness

8.4.3 Glazing and floor area

The proportion of glazing to floor area increases with the age of the house (as shown in Figure 65).

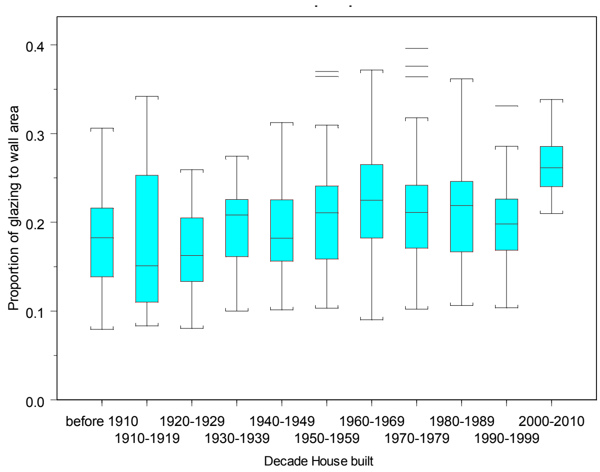

Figure 65: Glazing to wall area ratio by decade house built

However, there is more than just glazing influencing the increasing temperatures. There is a large increase in glazing in houses built from 2000 onwards which is not reflected in increasing temperature. Conversely, there is no increasing trend in glazing for the years 1950s to 1990s, yet indoor temperatures show an increase (see Figure 63).

Solar glazing (west, north and east-facing glazing) has been looked at separately, but there is no obvious relationship between large solar glazing areas and high temperatures.

Figure 66 shows an example of preliminary work with the solar glazing area as a proportion to floor area on the X-axis and the mean daytime living room temperature on the Y-axis. This graph plots just the 114 houses in the Auckland area, ensuring all the houses have a similar climate.

The expected pattern would be the higher the ratio of the solar glazing area to the floor area, the higher the living room temperatures. This is not the case in Figure 66.

The data has been explored regionally, using average and maximum temperatures achieved at different periods of the day. Orientation of the living room, shading, sunshine hours and the glazing in both the proportion to floor and wall area are just some of the possible influences that have been explored. However, each has shown little difference to the overall ‘flat’ pattern of temperatures as shown in Figure 66.

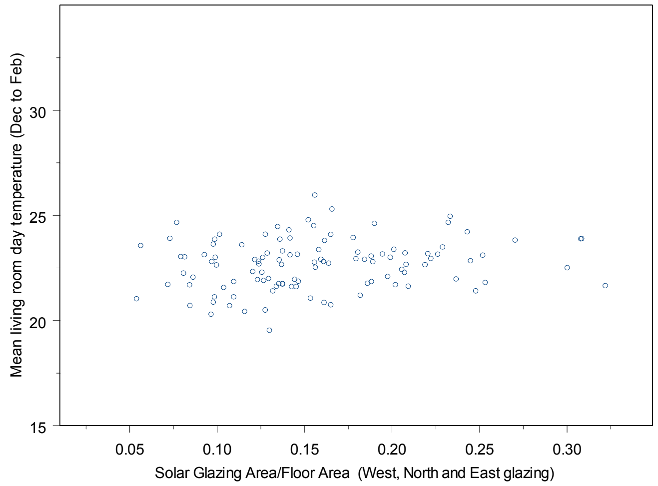

Figure 66: Solar glazing ratio vs. Auckland living room temperatures

One issue that remains to be explored is the influence of occupants. It may be possible that through the control of windows or fans (ventilation), and the control of shading, occupants have been able to limit the temperatures reached in their houses.

8.5 Temperature stratification in summer

Temperature stratification in the living room was looked at by examining influences on the two temperature loggers, which were placed at different heights.

Only two influences in summer were found to be statistically significant and neither explained more than 4% of the variation in temperature between the two loggers. The two influences found were the number of occupants recorded as living in the house (which is thought to relate to heat sources within the home), and the temperature difference between outside and inside. This re-enforces that the heating done inside is important as well as the climate or temperature difference between inside and outside during winter. The age of the house is not significant.

This work also showed the inside of the house is warmer than ambient on average in all the HEEP houses during the evening. The temperature inside is 1.3°C to 9.1°C warmer than outside in the evening.

8.6 Summer temperature discussion

This work has examined the HEEP summer (December to February) temperature data. As few New Zealand houses are cooled (air-conditioned) during the summer, this represents a large sample of naturally ventilated houses, with the ventilation controlled by the occupants' use of windows and doors.

Most houses (80%) spend less than one-quarter (that is, under two hours) of the summer daytime (9 am to 5 pm) with living room temperatures over 25°C. Most living rooms are between 20°C and 25°C for most of the time. As there has been no measurement of 'comfort' temperatures for New Zealand, it can only be assumed that based on overseas norms these would be comfortable.

On average, bedroom temperatures are lower than living room temperatures – by as little as 0.1°C in the morning (7 am to 9 am) and as much as 0.6°C during the day (9 am to 5 pm).

Inside temperatures have a smaller temperature range than the ambient, showing the temperature stabilising benefit of even low thermal mass construction.

Maximum temperatures are not only driven by solar radiation; the use of solid fuel burners led to indoor summer temperatures above 40°C in some houses. Excluding such houses, the maximum temperature is reached by 5.40 pm, although regional variation ranges from 5 pm (Auckland in the north) to 6.40 pm (Otago/Southland in the south). The variation is not a simple north to south issue, as other factors would be involved, including house age.

The house age (represented by decade of construction) and the local climate (the average external temperature over summer) have the largest impacts on the summer daytime living room temperatures. Together they explain 69% of the variation in mean summer living room day temperatures. A simple model has been prepared based on these two variables.

The mean summer living room temperatures show a trend of increasing by 0.25°C per decade. This gives a difference of 2.5°C between houses built at the beginning and the end of the 20th century.

Selected reasons for newer houses being warmer have been explored. The influence of house airtightness (occupant reported) has been found to be marginal, as has the presence of thermal insulation. No obvious relationship has been found between large areas of solar (west, north and east-facing glazing) and high temperatures.

Occupant influence also looks to be significant, but has not been quantified. Thermal calculation shows that houses behave differently without occupant influences; for example, opening and closing windows.

Although climate change is not a focus of this work, the local climate clearly influences the interior temperature. New houses are already warmer than older houses, so a 2-3°C temperature rise, possibly due to climate change, could make many of the newer houses uncomfortably warm. This problem is amplified with the houses that are being built today being 2.5°C warmer than those built a century ago. There is the danger that the occupants of these newer houses could become reliant on air-conditioning, with the resulting higher energy use forming a positive feedback loop into the mechanism of climate change. This is clearly an undesirable result.

9. EXTENSIVE TEMPERATURE MONITORING IN ONE HOUSE – CASE STUDY

Winter space heating is a large component of the energy used in New Zealand houses. The energy needed is determined by the climate, the physical properties of the building and the comfort expectations of the occupants.

Purchased heat requirements for a building can be reduced with appropriate design that looks to make effective use of the available solar radiation.

This section describes the investigation into a typical New Zealand house to assess the impact of solar radiation on indoor temperatures within that house.

9.1 The chosen typical house

The chosen house was built in Palmerston North in the early 1970s with a design common at that time, as shown in Figure 67.

Figure 67: Palmerston North House

The house is timber-framed with a stud height of 2.4 metres, suspended timber floor, timber windows and a galvanised iron roof. The house is uninsulated. The northern and eastern exterior walls have brick veneer cladding. The living room is located centrally within the house, with large windows in the northern wall as shown on the left of the photo.

9.2 Experimental set-up

Measurements of the indoor temperature within the living room were made for two periods of 25 days; one starting from the 20th May 1999 and the other from the 1st September 2000.

For the 1999 case, an intensive investigation of the living room temperatures was made. Eighteen temperature loggers were placed around the living room, including two placed in the centre of the room (at a height of 1.9m), three and four loggers placed at differing heights in the south-west and north-west corner of the room to provide information on the vertical temperature patterns within the room and three loggers along each of the southern and eastern walls. The eastern wall had a flued, radiant, natural gas heater. A temperature logger placed on the top of the heater provided an indication of when the heater was being used.

For the 2000 case, the interest was in examining the vertical temperature patterns, so only the vertical temperature array in the south-west corner was used. This array had temperature loggers placed at heights of 0.4 m, 0.9 m, 1.4 m and 1.9 m, however because of configuration problems no data was available from the temperature logger placed at 0.4 m.

The space heating used within the living room changed between the two periods monitored. The flued, radiant, natural gas heater used in 1999 was replaced in 2000 with a flued, flame-effect, convective, natural gas heater.

Temperature loggers were set with a five-minute interval between readings. Additional hourly measurements, covering the same time periods, of external air temperature and global horizontal solar radiation were extracted from the NIWA climate database (Penney 2003) taken from Palmerston North Airport, about 4 km to the north-east of the house. The global horizontal solar radiation reported in the NIWA database is the solar radiation received (in M Jm^{-2}) for the previous hour.

9.3 Results

Hourly measurements for the first nine days of the 1999 data are shown in Figure 68.

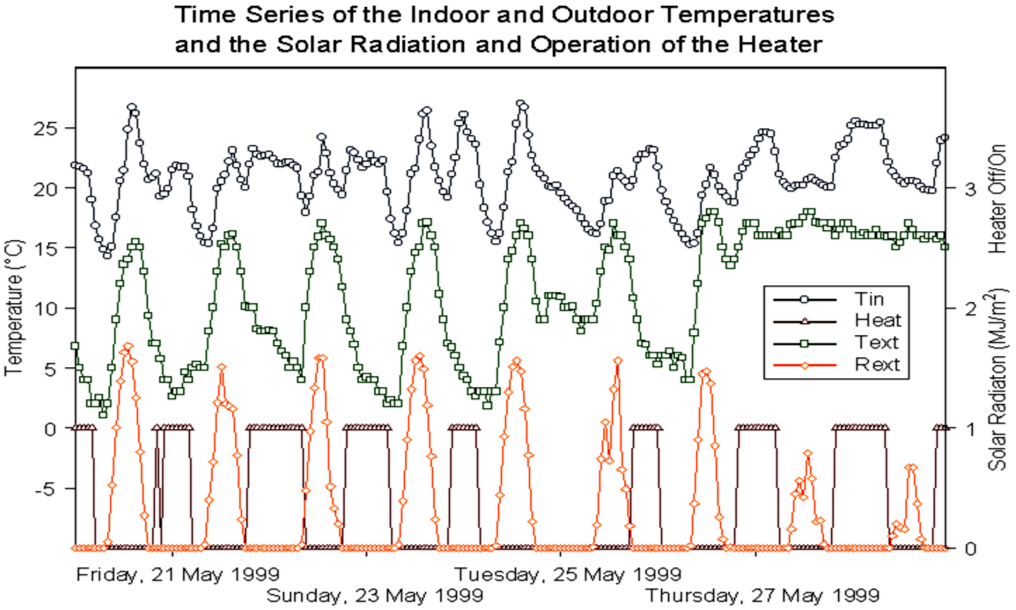

Figure 68: Measured parameters

For Figure 68:

Tin = *temperature reported by temperature logger at centre of room (°C)*
Text = *temperature recorded at airport (°C)*
Rext = *global horizontal radiation also recorded at airport (W/m^2)*
Heat = *indicator variable of whether heater was on or off.*

It can be seen that the occupants of the house use the radiant gas heater in the evenings and there is little overlap between the times of the solar radiation and heater operation.

To examine the average effect of the solar radiation, the gas heater use and the external temperature on the indoor temperature achieved within the house, an average for each of these variables was calculated for each hour of the day over the twenty-five day period. These average daily profiles are shown in Figure 69.

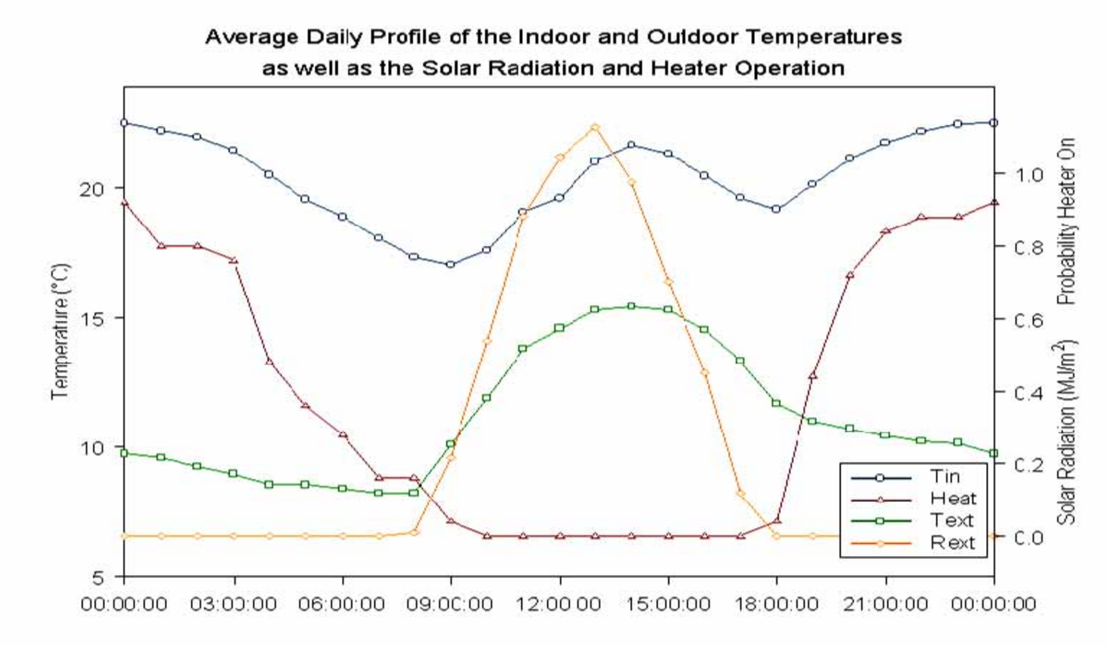

Figure 69: Average daily profile

As shown in Figure 69, the occupants frequently run the gas heater between midnight and 6am[13]. It can also be seen that peak solar radiation occurs before peak indoor temperature, suggesting that solar radiation has a delayed effect on indoor temperature. From a cross-correlation between indoor temperature and solar radiation, it was seen that maximum correlation occurs between the variables when a lag of two hours was applied to the solar radiation.

A multiple regression of the hourly indoor temperature was examined against the operation of the heater, the external temperature and the solar radiation lagged by zero, one, two or three hours. A lag of two hours provided the best fit with a multiple r^2 value of 0.68.

The fitted function was:

$$T_{in(t)} = 15.03 + 5.02 \cdot Heat_{(t)} + 0.25 \cdot T_{ext(t)} + 2.40 \cdot R_{ext(t-2)}$$

Equation 14: Hourly indoor temperature and solar radiation

The peak of the average solar radiation occurs at 13:00 and has a value of 1.13 $\mathrm{MJ\,m^{-2}}$. The solar radiation then has an average effect of about 2.7°C on the indoor temperatures recorded at 15:00. The measured solar radiation at 13:00 varied from a value of 0.16 $\mathrm{MJ\,m^{-2}}$ to 1.68 $\mathrm{MJ\,m^{-2}}$ corresponding to an average solar contribution to the 15:00 indoor temperature of between 0.4 °C and 4.0 °C.

Improvements to the accuracy of Equation 14 could be made by better accounting for the deviation between the measured values of the external temperature and solar radiation and the conditions influencing the temperature within the living room. For example, restriction of solar radiation in the afternoon because of shading from the north-eastern bedroom walls has not been considered.

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[13] It should be noted that the occupants were in full time employment and were away from the house during most of the day.

9.4 Vertical temperature distribution

From the measurements in 1999, a systematic variation in temperature within the living room can be seen that could be related to the height of the temperature measurement. From the literature, it has also been found that the type of heating employed within the room impacts on the temperature distribution (Howarth, 1985; Inard, Bouia and Dalicieux 1996). However, the work described in the literature has been conducted in laboratories, and considers static situations when a particular heater is running. Heating because of solar radiation is time dependent, and field measurements are needed to account for such factors as external shading, furnishings, and occupant interactions such as closing curtains or shutters.

A large amount of data has been collected from the vertical temperature measurements taken in the Palmerston North house. Figure 70 shows four days of measurements from 1999, and Figure 71 shows six days of measurements taken during 2000. In these graphs, time is shown 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, shows the temperature in 1°C increments. There is a horizontal line marking a height of 1.1m.

Figure 70 and Figure 71 show that, as the living room is being heated because of either heater operation at night or solar radiation during the day, there is an increase in the vertical temperature difference (indicated by more temperature layers) between the high sensors and the low sensors.

When the living room cools, because of heat conduction through the walls and infiltration heat losses, the vertical temperature difference is lessened. The most striking contrast between the temperature measurements for 1999 and 2000 is the change in the vertical temperature differences during heating. The convective heater, in use in 2000, produces greater vertical temperature differences than the radiant heater in use in 1999.

Examining the twenty-five day periods hour by hour gives the interval between 9pm and 1am as the time when the range of the vertical temperature differences is the smallest. This is the time when heating is most consistently applied.

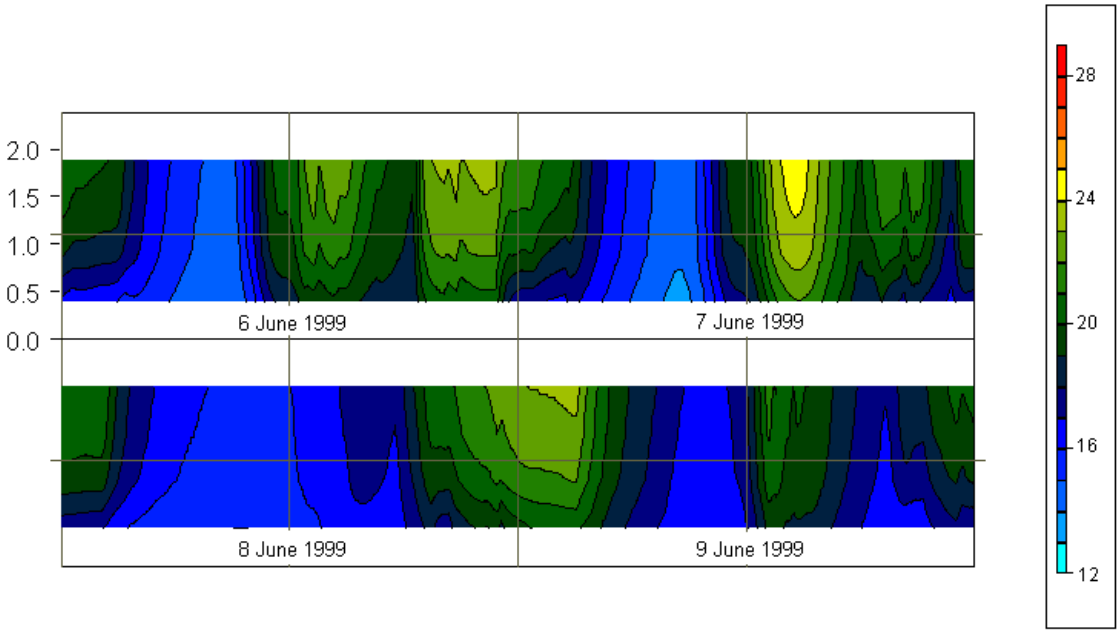

Figure 70 Vertical temperature stratification, 1999 (living room south-east corner)

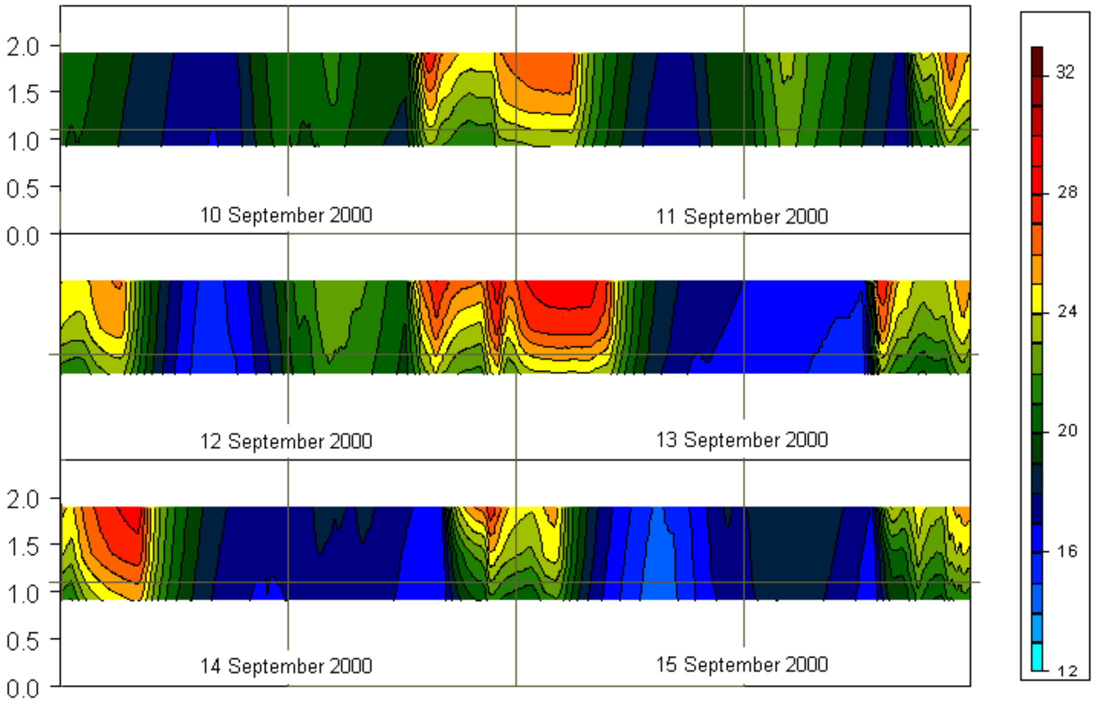

Figure 71: Vertical temperature profile, 2000 (living room south-east corner)

For 1999 (radiant heating) the temperature difference between the temperature logger at 1.9 m and the temperature logger at 0.9 m was typically between 1.0 °C and 2.0 °C with an average of 1.3°C. During 2000 (convective heating) the vertical temperature difference was typically between 3.0 °C and 7.0 °C with an average of 3.6 °C.

When the building cools, the vertical temperature difference drops to below 0.6 °C and is more sensitive to individual heating events. In the afternoon the temperature difference because of solar radiation, between 1pm and 3pm, ranges between 0.2 °C and 1.5 °C and has a consistent average of around 0.7 °C for both 1999 and 2000. The layering of the afternoon temperatures is similar to that of the radiant heater.

The estimated head height of a seated individual (1.1 m) is taken as a reference height. Table 49 gives the average estimated temperatures (as well as their standard deviations) at this height for the period of solar gains and the period of evening heating for 1999 and 2000. The afternoon solar gains produce similar temperatures between the two years, which are only slightly lower than the temperature measured during the evening heating for 1999 (radiant heating). Therefore, the temperature the solar radiation provides appears to be within the preference temperature range of the occupants.

Year	*Between 13:00 and 15:00*	*Between 21:00 and 01:00*
1999 (radiant)	20.6 ± 2.2 °C	20.8 ± 1.4 °C
2000 (convective)	20.3 ± 2.4 °C	22.3 ± 1.7 °C

Table 49: Temperatures during afternoon solar gains and evening heating

The temperatures measured during the evening heating for 2000 (convective heating) are, on average, about 1.5 °C warmer than the evening heating for 1999 (radiant heating). The occupant's commentary on the change of heating was that the new flame effect convective heater was less noticeable while in operation. They reported that the difference in temperature between the living room and other rooms of the house is obvious when they move between rooms. This difference in temperature may be because of differences in comfort between radiant heating and convective heating, or it may be that the assumption that the height influencing comfort is head height (1.1 m) is incorrect. A lower height, closer to the centre of the body, may be a better reference height. It is interesting to note that an energy conservation programme in Ireland needed to make corrections to the temperatures recorded at high locations (0.1 m from the ceiling) depending on the nature of the heating system (Fuller and Minogue 1981).

9.5 Conclusions

Indoor temperatures within buildings are dynamic. The vertical temperature distribution within the living room of the house under investigation was seen to depend on the nature of the heating system employed.

Convective heating produced a greater vertical temperature difference (3.6°C) than radiant heating (1.3°C). The solar gains were seen to produce a radiant effect on the afternoon temperatures within the living room, producing a vertical temperature difference approximately between 0.2°C and 1.5°C, with an average value of 0.7°C. The afternoon temperatures were comparable to the evening temperatures when the radiant heater was used (1999).

10. PENSIONER HOUSING – TEMPERATURE CASE STUDY

From February 2000 to January 2001, sponsored by the WEL Energy Trust, a group of 12 pensioner houses in Hamilton were monitored, as well as the 17 Hamilton HEEP houses. As well as full monitoring, a comprehensive survey and building audit were carried out, with monitoring of total energy use, hot water energy use, LPG heating, and bedroom/living room temperatures. One of the aims was to explore suppositions about heating by the elderly, such as:

- *superannuitants don't heat their houses because 'that's the way they have been brought up'. However the opposite theory is also available: 'Superannuitants want warmer houses because of their age and medical conditions.'*

10.1 Temperatures

The average evening temperatures (6pm-10pm) for each month of the year for the Hamilton houses in the study are given in Table 50:

	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
Pensioner	24.4	25.1	24.3	22.6	21.4	20.3	20.7	20.4	20.3	21.0	21.1	23.6
Standard deviation	*0.4*	*0.4*	*0.3*	*0.5*	*0.6*	*0.5*	*0.6*	*0.6*	*0.6*	*0.5*	*0.5*	*0.4*
Non-Pensioner	24.7	24.9	23.6	21.1	20.1	18.9	18.9	18.5	19.1	20.3	20.5	23.7
Standard deviation	*0.3*	*0.5*	*0.4*	*0.19*	*0.4*	*0.5*	*0.4*	*0.4*	*0.3*	*0.3*	*0.3*	*0.2*

Table 50: Average monthly living room evening temperatures in Hamilton houses (°C)

For the winter months (May-August), the pensioner living rooms are from 1.3 to 1.9°C warmer than the non-pensioner houses. These differences are significant. Most of the pensioner houses maintained average evening temperatures of around 20°C or more in the winter months. In the summer months, there is no significant difference in living room temperatures between the pensioner and non-pensioner houses.

For the bedrooms, Table 51 shows the average overnight (1am to 5am) monthly temperatures. During the winter months, the pensioner bedroom temperatures are on average 1.3-1.7°C warmer than the non-pensioner houses.

	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
Pensioner	21.4	22.5	21.1	19.4	17.8	15.8	16.4	15.3	16.1	17.7	18	21.3
Standard deviation	*0.3*	*0.3*	*0.3*	*0.3*	*0.4*	*0.4*	*0.5*	*0.5*	*0.4*	*0.3*	*0.4*	*0.3*
Non-Pensioner	20.4	21.6	19.8	18.0	16.3	14.5	14.7	13.8	15.0	16.9	16.9	20.7
Standard deviation	*0.3*	*0.15*	*0.2*	*0.19*	*0.2*	*0.4*	*0.3*	*0.3*	*0.3*	*0.3*	*0.2*	*0.15*

Table 51: Bedroom overnight temperatures in Hamilton houses (°C)

The difference in temperatures is significant for all months of the year, so we can conclude that the overnight temperatures of bedrooms are on average (1.2 ± 0.1)°C higher than in non-pensioner housing, with larger differences in the winter months. In June, more than half of the pensioners achieved average bedroom temperatures over 16°C, which meets minimal WHO recommendations, in contrast to only 2 houses out of 17 in the general Hamilton population.

The Hamilton pensioners maintain higher winter temperatures in winter in the living rooms during evenings, and overnight in bedrooms, than the general Hamilton population. This is despite the fact the income of the pensioners is low. The small size, relative thermal efficiency of the units, and wish for comfort are likely factors enabling the pensioners to maintain comfortable temperatures. Figure 72 and Figure 73

show the temperature range throughout the year for the family rooms of Hamilton pensioner and non-pensioner houses.

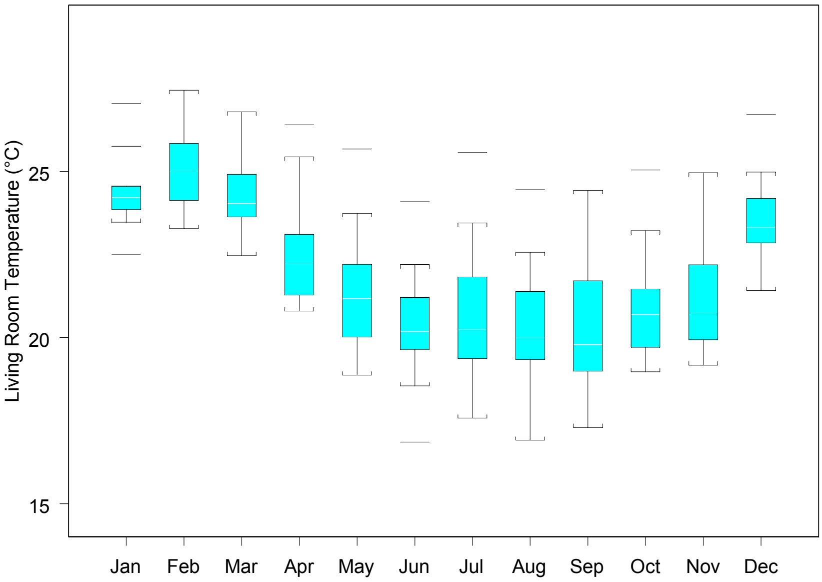

Figure 72 Hamilton pensioner family room evening temperatures

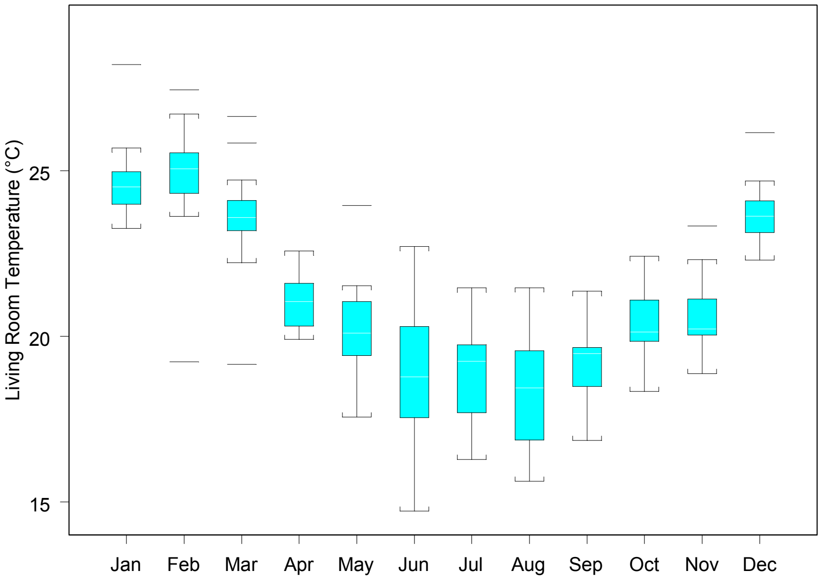

Figure 73 Hamilton non-pensioner family room evening temperatures

Eight out of the 12 pensioner units used portable LPG heaters, which have maximal heat outputs of more than 4 kW. Do these pensioners maintain higher temperatures because of larger heater output and lack of thermostat control?

The LPG heated pensioner houses were (1.6 ± 1.0°C) cooler than the other pensioner houses in the winter evening periods. This difference is not statistically significant, so we cannot draw any conclusion from this result.

The average income band reported for the pensioners was $15,000 to $20,000, compared with the rest of the Hamilton sample at just over $40,000. This infers that the average household income of the pensioners is about half that of the rest of Hamilton. The household sizes are also smaller, with either 1 or 2 occupants. In conclusion, the Hamilton pensioners in general maintain comfortable and healthy winter temperatures, and these are 1-2°C higher than the general Hamilton population.

10.2 Conclusions from the Hamilton study

The Hamilton pensioners in this study use more energy overall (including gas) per person than the non-pensioners, and slightly less energy for hot water per person.

Temperatures during winter in living rooms and bedrooms are 1-2°C higher in the pensioner houses. Most pensioners achieved comfortable and healthy temperatures, while many non-pensioners did not, especially in bedrooms. The higher temperatures in the pensioner housing may be because of the thermal efficiency of their well-insulated units, which need only about 500W of dedicated heating to maintain indoor temperatures 10°C above outside temperatures.

In contrast, a group of pensioners living in poorly insulated units in Wellington had evening living room temperatures 3.5°C colder than the Hamilton pensioners (even after insulation improvements), with average winter evening temperatures of about 17°C. It is probable the cost of heating affects the living room temperatures of pensioners.

The WEL Energy Trust pensioners are exceptional in that their units and hot water systems are highly thermally efficient, which makes a major contribution to both their low energy demand, and their indoor temperatures. Pensioners living in older, poorly insulated units or in houses would likely have a higher energy demand and costs, and lower indoor temperatures as heating would be less affordable and less effective. In summary:

- Using M-co wholesale prices (excluding transmission and distribution charges), the average kWh electricity costs the same for the Hamilton pensioner and non-pensioner houses
- Hamilton pensioner houses use **more energy overall** (including gas) per person than Hamilton non-pensioner houses, and **slightly less energy for hot water** per person
- Winter living room and bedroom temperatures are 1°C to 2°C higher in the pensioner houses, compared with the non-pensioner Hamilton houses. The Hamilton pensioner houses do have higher levels of thermal insulation, needing about 0.5 kW of heating to maintain the indoor at 10°C above outside temperatures. Following insulation improvements, Wellington pensioner units still had living room temperatures 3.5°C colder than the Hamilton units.

11. SOCIAL ANALYSIS - INTRODUCTION

The social analysis aspect of HEEP has evolved throughout the study and has several streams. These are outlined in detail in Sections 12 to 15

First (Section 12) is a description of the socio-demographic characteristics of the HEEP households.

Second (Section 13) is an analysis of the associations between household characteristics, energy use and thermal comfort as a contribution to the development of the HEERA model[14]. This analysis involved a systemic exploration of which household variables were necessary components of a scenario model that allows energy consumption to be calculated under a range of different conditions. The development of the HEERA model had been an objective of HEEP from its early conception.

Third (section 14) is a focus on energy access and social well-being. The first prong of this focuses on fuel poverty in New Zealand. The second prong is a response to the vulnerability of Maori households to deprivation, exposure to poor housing and their over-representation among households at health risk. It explores the extent to which Maori households might differ from other households in their energy use patterns and the benefits they receive from energy expenditure. The third prong focuses on solid fuel and is particularly concerned with the social impacts of interventions that push households away from using solid fuel in an attempt to improve air quality. Unlike the analysis of social variables for the HEERA model, these analyses are an example of HEEP being able to respond actively to emerging policy issues and problems.

Finally (Section 15), summary findings are presented around some critical aspects of household energy use in the context of sustainability. Analyses are undertaken around hot water heating and around dwelling size, and are further examples of the way in which a robust platform of fundamental research can illuminate new questions and address new concerns. Both the hot water analysis and the dwelling size analysis reflect a significant evolution in public and policy thinking since HEEP was implemented. When HEEP began, energy saving and minimising both household and aggregate energy consumption were very much at the core of public concern. In the public mind at least, energy largely meant electricity. Over the least ten years, however, energy conservation has become embedded within a broader conception of sustainability which is concerned with minimising the use of other resources – in particular, water. Moreover, the idea of sustainability itself has shifted from the bio-physical environment and the use of bio-physical resources to embracing social, economic and cultural resources and resilience.

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[14] See Section 6 for a more detail on the HEERA model

12. SOCIO-DEMOGRAPHIC CHARACTERISTICS OF HEEP HOUSEHOLDS

Prepared by Kay Saville-Smith and Ruth Fraser

As well as monitoring indoor temperature, energy use, and energy consumption behaviour, socio-demographic data was also collected for the 394 HEEP households.

12.1 Household type

The predominant household compositional type was the 'couple-with-children' household (35.7%), followed by 'couple-only' households (31.1%), and 'one person' households (13.3%). Figure 74 compares the household composition profile of the HEEP households with New Zealand households as recorded in the 2001 Census and the 2006 Census.

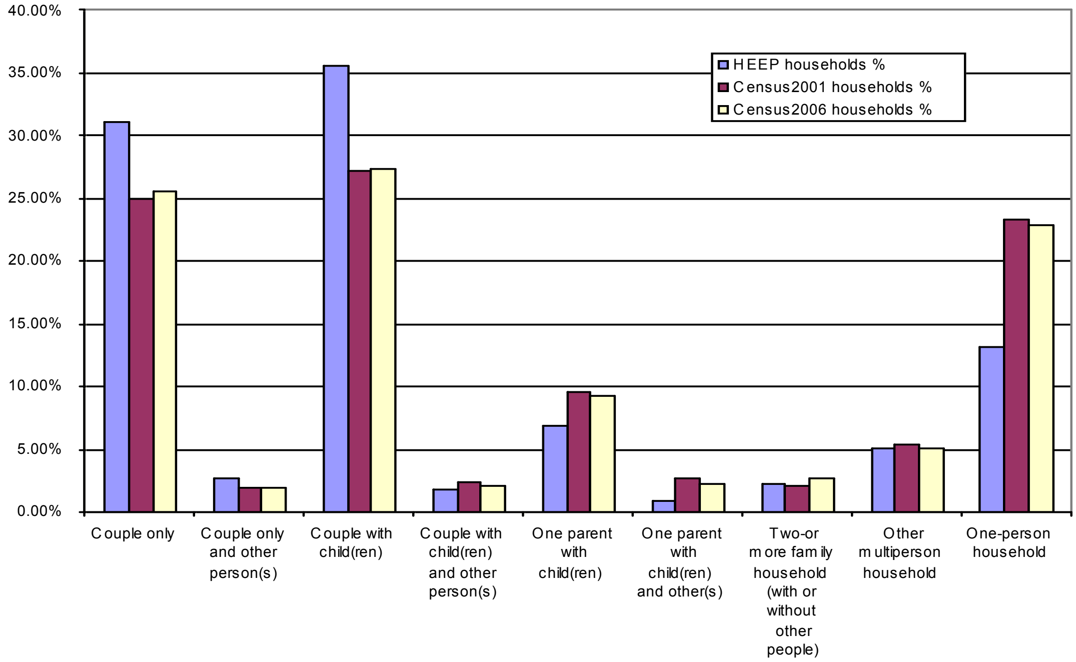

Figure 74: HEEP and 2001 Census and 2006 Household Composition

Similar proportions of HEEP households can be described as being in 'dependency' life stages, either because they have members who are under five years of age (15.2%) or because all members are 65 years or older (16.1%).

Figure 75 sets out the profile of households in relation to critical life stages associated with the youngest household member.

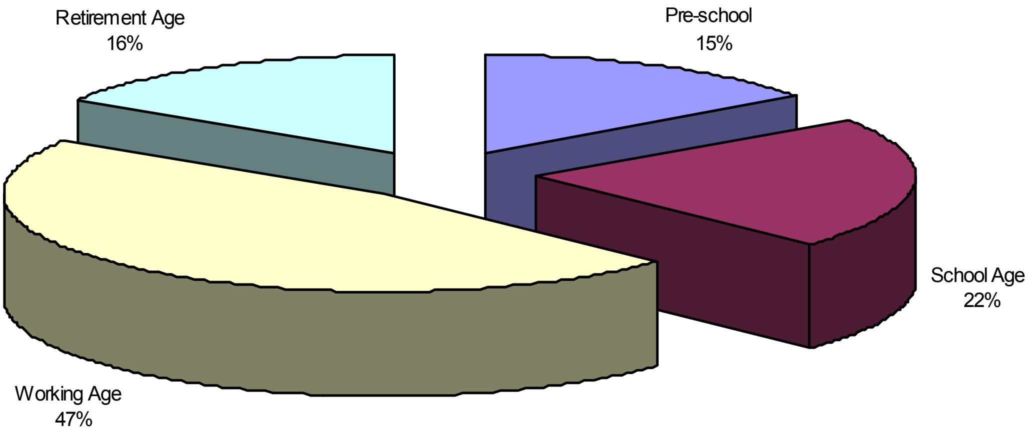

Figure 75: Age of youngest HEEP household member

Just over a quarter of households had no adult member in employment (25.5%), while 17.3% were households in which all the adult members were in full-time employment. The other largest category of households was those in which there was a mix of adults in full-time employment and not in employment.

12.2 Household income

Household income is calculated by combining the annual personal income for all household members. For analytic purposes, equivalised household income is a more robust measure because it takes into account household size. The most sensitive and complex equivalence scale used in New Zealand is the Revised Jensen Scale (RJS) (Jensen and Vasantha, 2001). Its data requirements exceed those provided through HEEP. Instead, we have used the 'Luxembourg Income Study (0.5) Scale' (LIS) (Atkinson et al, 1995). The LIS Scale is increasingly being used overseas and shows similar results to those generated by the RJS. The LIS scale adjusts equivalised household income by dividing annual household income by the square root of the number of persons in the household.

The Luxemburg method gives equivalised income quintile boundaries for the HEEP households of:

- Quintile 1 – less than or equal to $15,653
- Quintile 2 – $15,654 to $24,749
- Quintile 3 – $24,750 to $35,000
- Quintile 4 – $35,001 to $49,498
- Quintile 5 – over $49,499.

If household types were randomly distributed, then there would be equal numbers of each in each quintile, but this is not the case. The following HEEP household types are over-represented among the lowest household income quintiles if a normal distribution is assumed:

- one-person households
- other multi-person households
- one-parent with child(ren) households
- multiple family with children households
- couple-with-children plus others households
- couples with others households.

The latter are also over-represented in the highest income Quintile 5. Couple-with-children households tend to be over-represented in Quintiles 2, 3 and 4.

When considering life stages, the situation in relation to income quintiles is somewhat more mixed. Figure 76 shows the quintiles for equivalised household income for households in each life stage calibrated by youngest household member. Retired person households tend to be over-represented among income Quintiles 1 and 2. Households with pre-school and school aged children tend to be over-represented in income Quintiles 1 and 2. Households entirely made up of working age members tend to be over-represented in income Quintile 5.

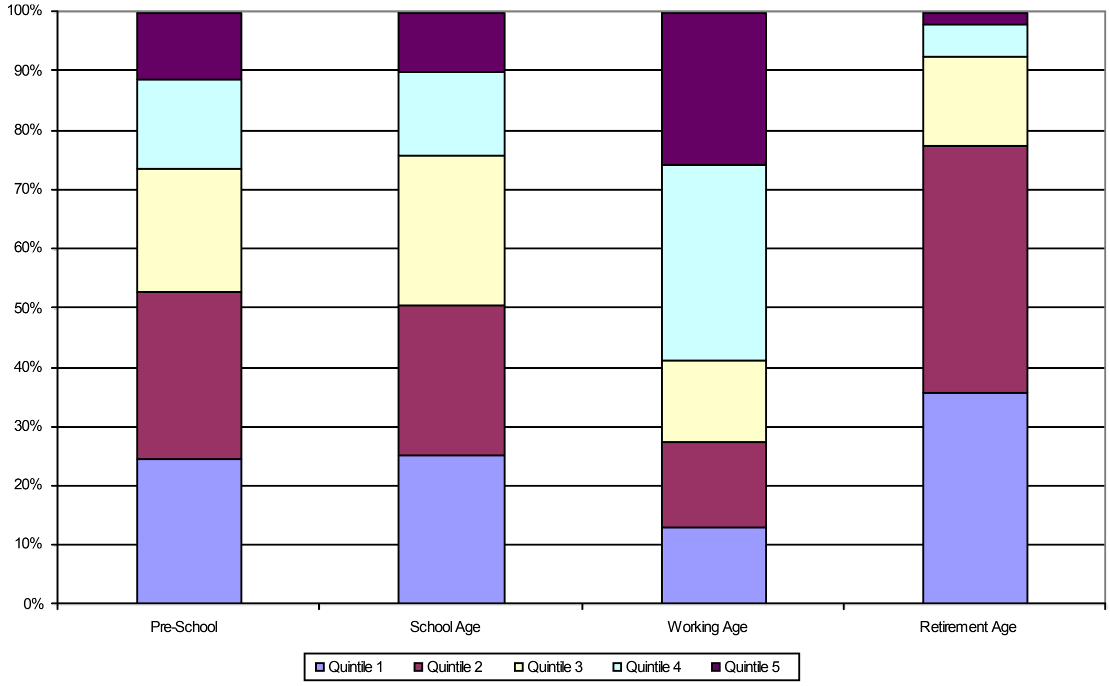

Figure 76: Equivalised HEEP household income by youngest household member

13. HOUSEHOLD VARIABLES AND FORECASTING AGGREGATE ENERGY USE

The HEERA model is a scenario model that allows energy consumption to be calculated under a range of different conditions. The social interactions and mediating factors that may give rise to particular energy use patterns and household temperature outcomes are complex.

To assist development of HEERA, the social analysis part of HEEP has focused on social and economic characteristics of HEEP households for which there are also significant and accessible time series of national data. The major sources of social and economic data relating to households and household members that have an extended time series are:

- dwelling and population census
- household economic survey
- household labour force survey.

Therefore, the main variables for which we tested correlations of energy use and indoor temperatures were:

- household characteristics such as:
    - size
    - type
    - life stage
- household economic status such as:
    - income sources
    - income
    - employment status.

13.1 Income, living room temperatures and energy use

In Year 9 we furthered previous analysis by exploring more rigorously the relationships between the following variables:

- equivalised income
- temperature – supplied from the direct monitoring of house temperatures in HEEP dwellings (units: °C). The temperature variable is the calculated mean winter evening living room temperature (5pm to 11pm, June to August).
- energy use – a variety of energy use variables were constructed based on monitoring use data (units: kWh per year):
    - total energy use: total annualised gross energy for all fuels
    - heating energy use: estimated annualised gross energy used for heating
    - Domestic Hot Water (DHW) energy use: estimated annualised gross energy used for hot water
    - residual energy use: estimated annualised gross energy used for non-heating and non-domestic hot water purposes, e.g. lighting and cooking.

All these are scale variables. Statistical descriptive measures of the six variables are shown in Table 52.

Variable		Equivalised Income Using LIS scale	Mean Winter Evening Living Room Temperature	LOG Total Energy Use	LOG Heating Energy Use	LOG DHW Energy Use	LOG Residual Energy Use
N	Valid	353	386	330	320	369	339
	Missing	41	8	64	74	25	55
Mean		$31,394	17.8	3.98	3.33	3.45	3.52
Std. error of mean		$908	0.121	0.012	0.031	0.012	0.016
Median		$27,500	17.75	3.99	3.41	3.45	3.56
Mode		$49,498	17.2	3(a)	1(a)	3(a)	1(a)
Std. deviation		$17,060	2.37	0.22	0.56	0.23	0.29
Skewness		0.545	-0.017	-0.26	-1.39	0.09	-1.89
Kurtosis		-0.440	0.2	0.48	3.55	0.06	13.17
Range		$88,883	13.8	1	4	1	3
Minimum		$1,118	10.0	3	1	3	1
Maximum		$90,001	23.8	5	4	4	4

Table 52: Income, living room temperature and energy use descriptive statistics

Note: (a) Multiple modes exist. The smallest value is shown.

Three sets of analysis were undertaken in relation to the equivalised income, temperature and energy variables. Subsequent to descriptive analysis, a correlation test was performed to identify any statistically significant relationship between each pair of variables. Where a statistically significant correlation was found, regression analysis was used to model the relationship between the variables. The latter was directed to assessing the strength of the relationship and the potential for that relationship to contribute to HEERA as a forecasting model.

13.1.1 Equivalised income and mean living room temperature

There was no statistically significant correlation found between equivalised income and mean living room winter temperatures.

13.1.2 Equivalised income and energy use

The extent to which equivalised income had a statistically significant correlation with energy use varied, and is set out in Table 53. For total energy use, DHW and residual energy use, statistically significant correlations emerged. In relation to heating energy use, no statistically significant relationship was found.

Correlation Variables	Pearson Correlation Statistic
Equivalised income and total energy use	0.147*
Equivalised income and energy use for heating	0.116
Equivalised income and energy use for DHW	0.142*
Equivalised income and residual energy use	0.121*

Table 53: Correlations equivalised income and energy use variables

Note: * Correlation is significant at the 0.05 level (2-tailed)

Although there are statistically significant relationships between equivalised income and some energy use variables, the explanatory strength of those relationships is not particularly strong.

Table 54 sets out the regression analysis results for:

- equivalised income and total energy use
- equivalised income and hot water energy use
- equivalised income and residual energy use.

It shows that equivalised income explains only around 2% of the variation in total energy use. Equivalised income explained less than 2% of the variance for both hot water energy use (1.7%) and residual energy use (1.8%).

Model	Predictor Variable	Dependent Variable	R-square	Adjusted R-square
1	Equivalised income	Log total energy use	0.022	0.018
2	Equivalised income	Log hot water energy use	0.020	0.017
3	Equivalised income	Log residual energy use	0.021	0.018

Table 54: Paired model summaries equivalised income and energy variables

The adjusted R-square value indicates the loss of predictive power or shrinkage and is generated by the SPSS computer programme. The R-square indicates the amount of the variance that is accounted for by the regression model from our sample; the adjusted values tells how much variance would be accounted for if the model had been derived from the population from which the sample was taken (Field, 2000).

13.2 Size of household, living room temperatures and energy use

The HEEP Year 8 report (Isaacs et al, 2004) noted that preliminary analysis of the social data did appear to confirm the widely-held belief that the size of household is related to household energy use. We were interested in exploring whether household size also impacted on indoor temperatures. The variables used for this analysis are:

- **size of household** – two variables were constructed to address size of household impacts:
  - household size: the number of usually resident household members
  - occupancy: a constructed variable calculating crowding as a function of household size and total number of rooms. It is highly correlated to household size and initial testing shows that in most analysis household size appears to be the stronger variable. Occupancy has been calculated using the American crowding index – defined as the number of usual residents in a dwelling divided by the number of rooms in that dwelling (Statistics NZ, 2003). This index does not take into account the type of rooms in the dwelling or the age and sex of the usual residents.
- **temperature** – as described above (Section 13.1) (units: °C)
- **energy use** – as described above (Section 13.1) (units: kWh per year)

All these are scale variables. Their descriptive measures are set out in Table 55.

		Household Size	Occupancy	Mean Winter Evening Living Room Temperature	LOG Total Energy Use	LOG Heating Energy Use	LOG DHW Energy Use	LOG Residual Energy Use
N	Valid	394	393	386	330	320	369	339
	Missing	0	1	8	64	74	25	55
Mean		2.90	0.33	17.8	3.98	3.33	3.45	3.52
Std. error of mean		0.08	0.01	0.12	0.012	0.03	0.01	0.02
Median		3.00	0.29	17.8	3.99	3.41	3.45	3.56
Mode		2	0.22	17.2	3(a)	1(a)	3(a)	1(a)
Std. deviation		1.5	0.19	2.4	0.22	0.56	0.23	0.29
Skewness		1.32	2.71	-0.02	-0.26	-1.39	0.09	-1.89
Kurtosis		3.23	16.92	0.2	0.48	3.55	0.06	13.17
Range		10	1.92	13.8	1	4	1	3
Minimum		1	0.08	10.0	3	1	3	1
Maximum		11	2.00	23.8	5	4	4	4

Table 55: Household size, living room temperatures and energy use statistics

Note: (a) Multiple modes exist. The smallest value is shown.

13.2.1 Household size and mean living room temperature

There was no statistically significant correlation found between household size and mean living room winter temperatures.

13.2.2 Household size, occupancy and energy use

The extent to which household size and occupancy had statistically significant correlations with energy use varied. For total energy use, DHW and residual energy use, statistically significant correlations emerged. Household size showed the highest correlation. In relation to heating energy use, Table 56 shows that no statistically significant relationship was found.

Correlation Variables	Pearson Correlation Statistic
Household size and total energy use	0.357**
Household size and energy use for heating	0.092
Household size and energy use for DHW	0.513**
Household size and residual energy use	0.307**
Occupancy and total energy use	0.205**
Occupancy income and energy use for heating	0.058
Occupancy income and energy use for DHW	0.339**
Occupancy income and residual energy use	0.121*

Table 56: Correlations equivalised income and energy use variables

Note: Correlation is significant at the: * 0.05 level (2-tailed). ** 0.001 level (2-tailed)

Table 57 sets out the results from the regression analysis for:

- household size and total energy use
- household size and heating energy use
- household size and residual energy use
- occupancy and total energy use
- occupancy and heating energy use
- occupancy and residual energy use.

Table 57 shows that household size explains around 17% of the variance in total energy use. In relation to hot water energy use, household size explains 26% of the variance. Household size explains only 9% of residual energy use.

Model	Predictor Variable	Dependent Variable	R-square	Adjusted R-square
1	Household size	Log total energy use	0.173	0.170
2	Household size	Log hot water energy use	0.264	0.261
3	Household size	Log residual energy use	0.094	0.091
4	Occupancy	Log total energy use	0.060	0.057
5	Occupancy	Log hot water energy use	0.108	0.106
6	Occupancy	Log residual energy use	0.014	0.011

Table 57: Paired model summaries household size, occupancy and energy variables

Occupancy has a lower explanatory power, explaining 11% of DHW energy use variance but only 1% of the residual energy use. It should be noted that both occupancy rate and household size are also highly correlated to each other (Pearson test, $r = 0.810$, $p<001$). Testing also shows a strong correlation between life stage (a factor variable) and household size (Spearman test, $r^2 = -0.738$, $p<0.001$).

13.3 Household life stage, temperatures and energy use

The impacts of life stage or life cycle on consumption, activity patterns and ways of life have been well-documented (e.g. Davey and Mills 1989, Davey 1993, Davey 1998, Pool 1995, Silva et al, 1994). To capture the impact of life stages in the context of domestic energy use in HEEP, we have constructed a life stage variable around the age of the youngest individual usually resident in the household.

In the HEEP Year 8 report we noted that there appeared to be some relationship between energy use and life stage. First, households whose youngest member is aged five to 14 years tended to be over-represented among the higher total fuel users while, by way of contrast, households whose members are all in excess of retirement years were over-represented among the lowest quintile of total fuel users. Figure 77 shows that pattern still prevails in the final data.

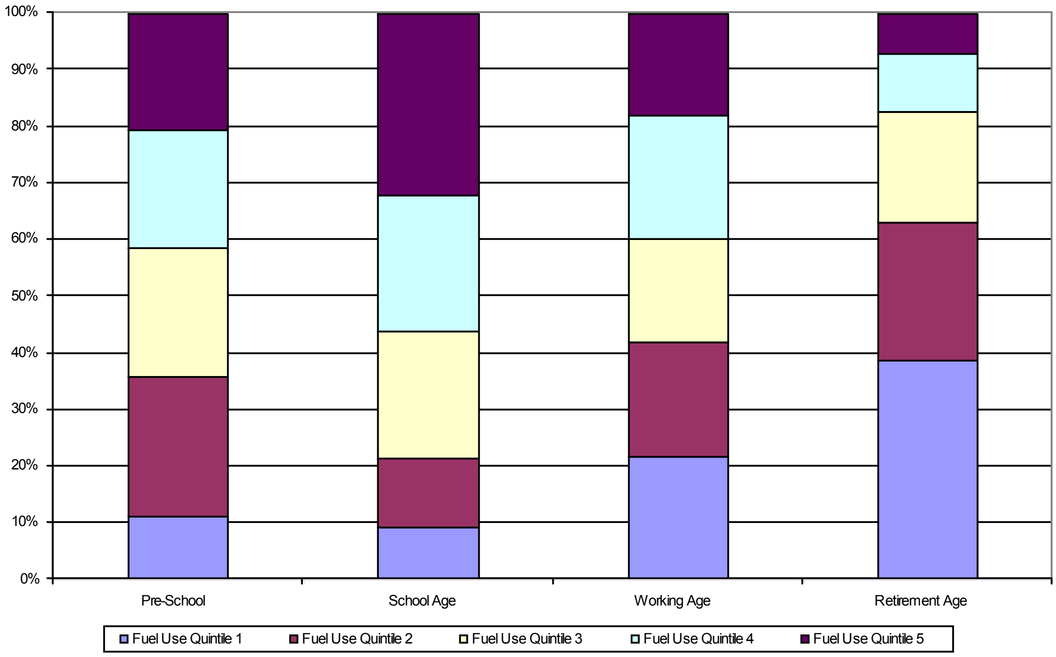

Figure 77: Total fuel use by age of youngest household member HEEP households

The variables used for this analysis are:

- life stage – this is a constructed variable based on the age of the youngest member in the household: pre-school age (0-4 years); school age (5-14 years); working age (15-64 years); and retired (65+ years)
- temperature – as described above (Section 13.1) (units: °C)
- energy use – as described above (Section 13.1) (units: kWh per year).

The majority of these are scale variables. The descriptive measures of the temperature and energy variables are set out in Table 52 and Table 55 above. Life stage is an ordinal variable. A frequency table for life stage is set out in Table 58.

Value		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Pre-school (0-4 years)	60	15.2	15.3	15.3
	school age (5-14 years)	86	21.8	21.9	37.2
	working age (15-64 years)	183	46.4	46.7	83.9
	retired (65+ years)	63	16.0	16.1	100.0
	Total	392	99.5	100.0	
Missing	missing (i.e. missing age data)	2	0.5		
Total		394	100.0		

Table 58: Frequency table of the life stage variable

13.3.1 Life stage and mean living room temperature

There was no statistically significant correlation found between life stage and mean living room winter temperatures.

13.3.2 Life stage and energy use

The extent to which life stage had a statistically significant correlation with energy use varied. For total energy use, DHW and residual energy use, life stage has a statistically significant correlation. Table 59 shows that in relation to heating energy use, no such statistically significant relationship was found.

Correlation Variables	Spearman Correlation Statistic
Life stage and total energy use	-0.271*
Life stage and energy use for heating	-0.053
Life stage and energy use for DHW	-0.346*
Life stage and residual energy use	-0.239*

Table 59: Correlations life stage and energy use variables

Note: * Correlation is significant at the 0.05 level (2-tailed)

Table 60 sets out the results from the regression analysis for:

- life stage and total energy use
- life stage and DHW energy use
- life stage and residual energy use.

The life stage variable explains around 10% of the variance in total energy use. In relation to hot water energy use, household size explains 17% of the variance. Life stage explains around 8% of residual energy use.

Model	Predictor Variable	Dependent Variable	R-square	Adjusted R-square
1	Life stage	Log total energy use	0.103	0.095
2	Life stage	Log hot water energy use	0.174	0.167
3	Life stage	Log residual energy use	0.088	0.080

Table 60: Paired model summaries for life stage and energy variables

13.4 The impact of social variables

Further analysis was undertaken through multiple regressions to test energy use in relation to all four social variables:

- equivalised income
- household size
- occupancy
- life stage.

Because of the close correlation between occupancy and household size, two multiple regressions were undertaken. One included occupancy and one excluded it. Table 61 shows the results for the multiple regression analysis.

Model	Predictor Variables	Dependent Variable	R-square	Adjusted R-square
1	Equivalised income, life stage, size of household, occupancy	Log total energy use	0.241	0.225
2	Equivalised income, life stage, size of household	Log total energy use	0.223	0.210
3	Equivalised income, life stage, size of household, occupancy	Log DHW energy use	0.324	0.311
4	Equivalised income, life stage, size of household	Log DHW energy use	0.328	0.318
5	Equivalised income, life stage, size of household, occupancy	Log lighting etc energy use	0.167	0.151
6	Equivalised income, life stage, size of household	Log lighting etc energy use	0.153	0.139

Table 61: Multiple regression analysis for social dynamics variables and energy use

As Table 61 shows, the explanatory power of these variable sets is not strong. When modelled together, the four selected social dynamic variables account for around 22-24% of the variance in total energy use. When the occupancy term is dropped from the analysis, the explanatory power of the model is reduced only slightly.

For DHW, the variable set including occupancy accounts for 31-32% of variance. The dropping of the occupancy variable from the set has little impact.

Similarly with residual energy use, when the occupancy variable drops out of the model the explanatory power is reduced, but only slightly. The four variable set explains 15-17% of the variance in residual energy use, while the three variable set (excluding occupancy) accounts for around 14-15% of the variance.

This simply confirms the strong correlation between household size and occupancy. The use of household size for HEERA purposes would thus provide a simple and reliable method of capturing the size effects of the population living within a single dwelling.

14. FUEL POVERTY, MAORI HOUSEHOLDS AND SOLID FUEL USAGE

In the final year of the research programme, the social analysis of HEEP data moved beyond exploring the correlations between social, energy and temperature variables for integration into the HEERA model. Instead, analysis concentrated on three areas of considerable policy concern:

- fuel poverty
- temperature and energy use in Māori households
- solid fuel usage.

14.1 Fuel poverty

Fuel poverty is indicated where:

- residents expend, or would be required to expend, excessive levels of their income on heating to achieve and maintain healthy indoor temperatures, and/or
- unhealthy indoor temperatures prevail because residents constrain energy expenditure to affordable levels, and/or
- residents are unable to achieve healthy indoor temperatures even where their heating expenditure constitutes an excessive proportion of income.

Internationally, there has been a consistent problem with the measurement of fuel poverty because few surveys into energy consumption and expenditure have measured temperatures within dwellings (Hunt and Boardman 1994). HEEP does precisely that and, in doing so, provides a unique evidential platform for grasping the nature of fuel poverty in New Zealand.

At its simplest, fuel poverty exists when households are not able to afford comfortable domestic warmth. Warmth, and more particularly *comfortable* warmth, is clearly a matter of subjective perception. There are, however, some critical thresholds around acceptable temperatures related to health. Temperatures that are:

- lower than 16ºC appear to impair respiratory function
- below 12ºC place strain on the cardiovascular system
- below 6ºC place people at risk of hypothermia (Collins 1986).

The impacts of low temperatures are exacerbated where individuals are vulnerable through illness, disability or age. Low temperatures also pose greater risks when exposure is for extended periods (Raw et al 2001). The World Health Organisation has concluded that the optimum indoor temperature is in the range 18ºC to 24ºC (WHO 2003).

The Working Group appointed by the Watt Committee on Energy in the United Kingdom recommends (Hunt & Boardman 1994):

- 21ºC for 13 hours a day in living rooms
- 18ºC for eight hours at night and an additional five hours during the day in bedrooms
- 18ºC for 13 hours a day in other spaces
- 14.5ºC in all spaces at all other times.

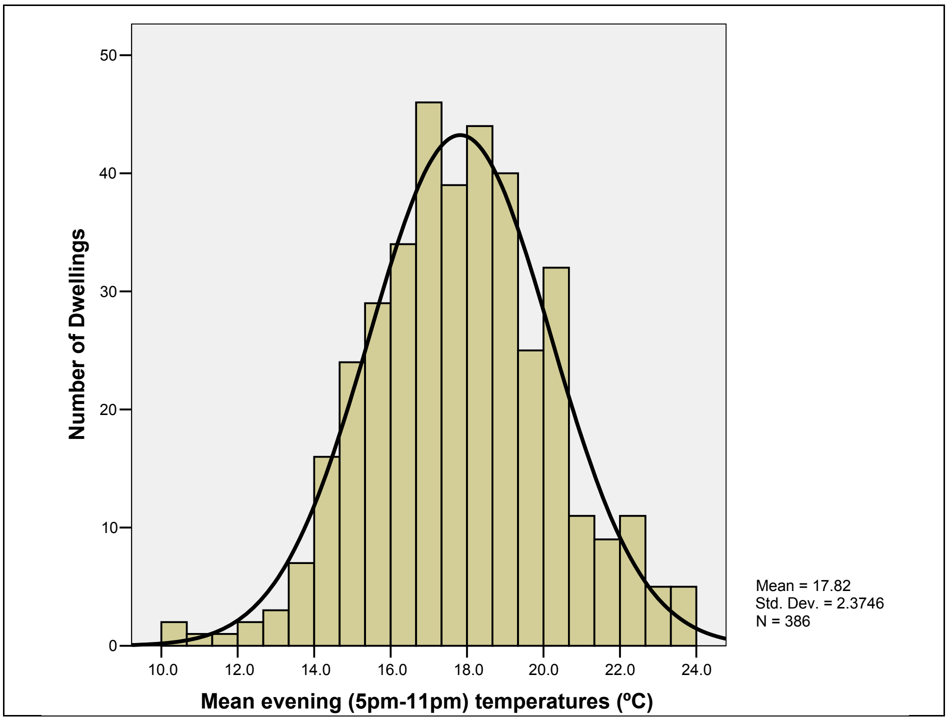

Figure 78: Winter evening living room average temperature distribution

Of the 386 HEEP dwellings for which mean winter evening living room temperatures could be calculated, only 68 (18%) had temperatures in excess of 20ºC and 34 (9%) over 21ºC. Figure 78 shows the distribution of winter living/family room mean evening temperatures among the HEEP dwellings. For Figure 78 the mean is 17.8, the standard deviation 2.37 and the count is 386.

The Luxemburg method (Atkinson et al 1995) has been used to calculate equivalised household income to control for household size effects. The equivalised income is calculated by dividing total household before tax income by the square root of the number of occupants. Table 62 gives quintile boundaries for the HEEP households:

Quintile	Boundaries
1	$1,118 - $15,653
2	$15,654 - $24,749
3	$24,750 - $35,000
4	$35,001 - $49,498
5	$49,499 - $90,001

Table 62: HEEP equivalised income quintiles

Table 63 shows that the below 16ºC dwellings are over-represented in the two lowest equivalised income quintiles.

Equivalised income quintiles	Mean evening living room temp less than 16°C		Mean evening living room temp 16°C or more	
	N	%	n	%
Quintile 1: <= $15,653	24	32.4	49	18.1
Quintile 2: $15,654-$24,749	19	25.7	62	22.9
Quintile 3: $24,750-$35,000	7	9.5	53	19.6
Quintile 4: $35,001-$49,498	13	17.6	62	22.9
Quintile 5: $49,499 +	11	14.9	45	16.6
Total	***74***	***100***	***271***	***100***

Table 63: Equivalised income by at-risk mean temperatures

Analysis by the number of occupants found that one-person households are also over-represented in the below 16ºC group, while households with 3-4 occupants tend to be under-represented in this group. Dwellings below 16ºC are also more likely to be accommodating tenant households rather than owner-occupiers.

These associations between below 16ºC mean evening winter temperatures in living rooms and income, household size and tenure respectively are statistically significant. Houses with very cold winter living room temperatures are also more likely to be situated in urban rather than rural areas (Table 64).

Variables: **Below 16ºC mean temperatures and:**	**Pearson chi-square statistic**	**DF**	**p-value**
Equivalised incomes (n=345)	10.1	4	0.038
Household size (n=386)	11.3	3	0.010
Tenure (n=386)	5.5	1	0.019
Location (n=386)	4.6	1	0.032

Table 64: Socio-demographic variables and winter evening living room at-risk (<16ºC) mean temperature

Table 65 summarises the proportion of average weekly expenditure for the seven groups and, for the 'Domestic fuel and power' sub-group, both the proportion and average weekly expenditure were reported in the Household Economic Survey (HES).

As household incomes increase, the proportion spent on domestic fuel and power decreases, from 5.3% for the 1st quintile to 2.2% for the 5th quintile. However, while the average income increases by 660%, the expenditure on fuel and power increases by only 65%.

HES income quintile	**1**	**2**	**3**	**4**	**5**
Lower end	Open	$23,000	$37,900	$58,900	$87,600
Upper end	$22,999	$37,899	$58,899	$87,599	Open
Average	$11,500	$30,450	$48,400	$73,250	$87,600
Expenditure group and sub-group					
Food group	17.0%	18.4%	16.3%	16.7%	14.5%
Housing group	24.0%	23.7%	26.0%	25.1%	23.5%
Household operation group	15.6%	14.7%	12.4%	12.1%	11.5%
Domestic fuel and power	**5.3%** **$43.80**	**4.6%** **$51.60**	**3.4%** **$54.60**	**2.8%** **$59.10**	**2.2%** **$72.20**
Apparel group	2.5%	2.1%	3.4%	3.2%	4.3%
Transportation group	13.9%	15.5%	16.7%	15.5%	16.7%
Other goods group	10.2%	10.3%	10.8%	11.7%	11.5%
Other services group	16.8%	15.3%	14.5%	15.7%	18.0%
Total net expenditure	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**

Table 65: HES average weekly expenditure by income group of household

The HES collects expenditure data but nothing on conditions, notably temperatures, within the houses. What the HEEP data reveals is that while low income households appear to value increased warmth, they are unable to achieve warm indoor temperatures (despite expending proportions of their income on energy which would be considered overseas to place the household in the fuel poverty category). Moreover, the higher proportionate expenditure of low income householders does not assure those households a warm house or even a warm living room.

HEEP finds that households in dwellings with very cold indoor temperatures during winter (under 16ºC) appear to spend a greater proportion of their income on energy than the HEEP households overall. The households with very cold living rooms on average expend 5.6% of income in winter on energy compared to on average 4.3% of income for the total set of HEEP households.

There is a statistically significant relationship between equivalised income and self-reported winter energy expenditure (Pearson test, r = -0.621, p<001). Among the lowest income quintile of HEEP households, 28% expended 10% or more of their monthly income on winter energy, but none of the top three quintiles expended in excess of 10% or more of their income (Table 66).

Equivalised income quintiles	**Winter energy expenditure <10% of monthly income**		**Winter energy expenditure ≥10% of monthly income**		**Total**
	n	%	n	%	
Quintile 1: <= $15,653	46	72	18	28	64
Quintile 2: $15,654-$24,749	65	97	2	3	67
Quintile 3: $24,750-$35,000	52	100	0	0	52
Quintile 4: $35,001-$49,498	60	100	0	0	60
Quintile 5: $49,499 +	48	100	0	0	48

Table 66: Equivalised income quintiles by winter energy expenditure – HEEP households

Higher proportions of energy expenditure do not appear to be a guarantee of warmer temperatures. Analysis of the HEEP data found that the mean living room winter evening temperature for households expending *less* than 10% of their monthly income on energy is 1.3ºC higher than households expending 10% or more on energy. Households expending less than 10% of income have an average mean evening living room temperature during the winter of 18.1ºC. This compares to 16.8ºC in dwellings accommodating households expending more than 10% of their incomes on electricity in the winter months.

HEEP data shows that households in dwellings with winter indoor temperatures under 16ºC appear to spend a greater proportion of their income on energy than the HEEP households overall. These households on average expend 5.6% of income in winter on energy compared to on average 4.3% of income for the total set of HEEP households.

14.2 Temperature and energy use in Māori households

The experience of the HEEP Māori households provides an opportunity to consider the importance of ethnicity as a determinant of energy end-use patterns, and the extent to which certain ethnic groups have particular energy end-use patterns because they tend to be over-represented in certain vulnerable socio-economic positions. The number of Māori households in HEEP is small and, consequently, the data cannot be statistically generalised to Māori households in New Zealand. This analysis of Māori households is largely descriptive, as the small sample size means that test variables have multiple categories and the cell sizes for the Māori households are too small to enable significance testing. Where the difference is statistically significant this is noted in the text.

Applying Statistics NZ's definition of a Māori household as one in which one or more members identify themselves as having Māori descent, there are 61 Māori households within the total HEEP sample of 394 households. Although HEEP is not a representative sample, the characteristics of the Māori HEEP households are consistent with national figures for Māori households. The Māori HEEP households tend to be larger and younger than the HEEP sample as a whole, and more likely to be over-represented among the lower income quintiles.

The number of people living in each of the 394 HEEP dwellings ranges from 1-11. While the range in size for Māori HEEP households is less (1-9 people), Māori HEEP households tend to be larger in size on average. The average household size for all households in the HEEP sample is 2.9, while the average household size for Māori households in the sample is 3.4.

The predominant household composition type in the 394 HEEP dwellings is the couple-with-children household. Those households make up 35.7% of the households, followed by couple-only households (31.3%) and one-person households at 13.3%. Data on household composition is available for 59 of the 61 Māori HEEP households. The predominant household composition type in the 59 dwellings with Māori HEEP households is the couple-with-children household (44.1%), followed by one-parent-children households (18.6%) and couple-only households (11.9%).

Figure 79 compares the household composition profile of all HEEP households with Māori HEEP households and with New Zealand households as recorded in the 2001 Census.

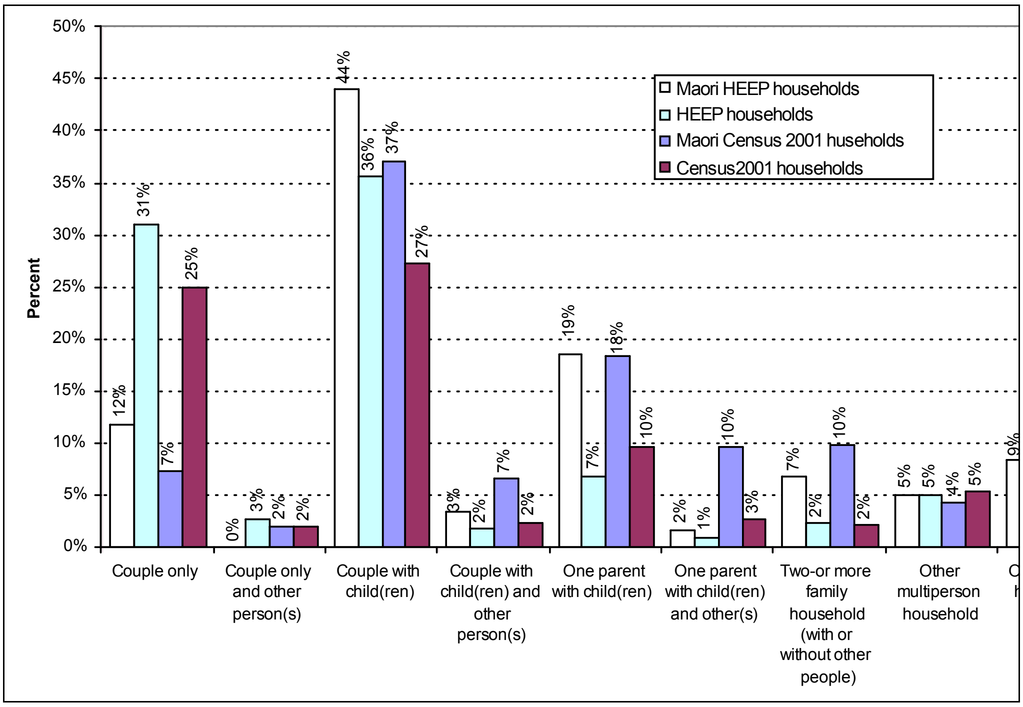

Figure 79: Household composition – HEEP & 2001 Census

Life stage analysis can be a useful tool for exploring assumptions about individuals or households by categorising them into groups based on criteria such as age or accomplishment of some life event, for instance graduating school or purchasing a first home. For the HEEP households there were some assumptions about the different behaviours of retired households compared to say households with young children. All HEEP households were divided into one of four life stages based on the age of the youngest person in the house. The four life stages are as follows:

- pre-school age (0-4 years)
- school age (5-14 years)
- working age (15-64 years)
- retirement age (65 years and over).

The household composition profile for Māori households within HEEP shows a higher proportion of households with young dependants. Around three-quarters (74.6%) of Māori

HEEP households have household compositions including children compared to less than half (47.7%) of all HEEP households.

The proportion of Māori HEEP households with youngest members in the school age (5-14 years) category is more than double the proportion of these households in the wider HEEP sample. Consequently Māori HEEP households have much lower proportions of households in the working age and retirement age life stage households compared to the HEEP sample as a whole.

Figure 80 sets out the profile of all HEEP households and Māori HEEP households in relation to critical life stages associated with the youngest household member.

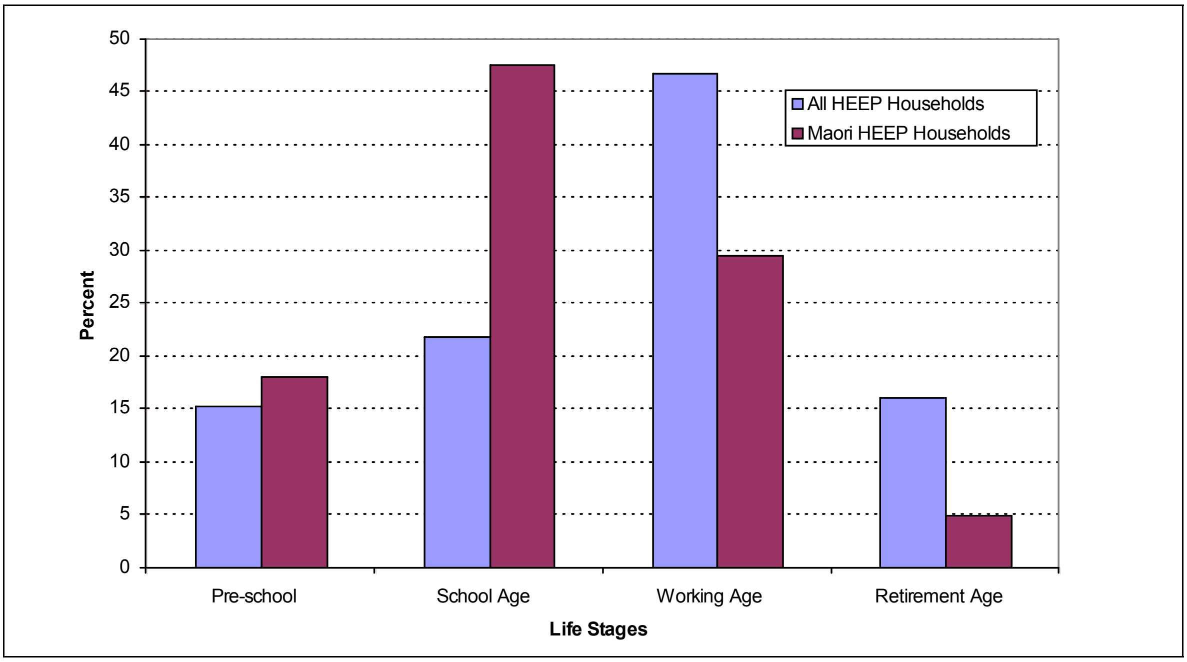

Figure 80: Age of youngest household member – all & Māori HEEP households

ust over a quarter of all HEEP households had no adult member (aged 15 or above) of the household in employment (25.3%), while 46.1% were households in which all the adult members were in employment. In the remaining households (28.6%) there was a mix of adults in employment and not-in-employment.

A fifth of Māori HEEP households had no adults in employment, while half were households in which all the adult members were in employment. The marginally higher proportion of Māori HEEP households with a household member in employment is likely to reflect the somewhat younger age structure of Māori households.

The Luxemburg method (Atkinson et al 1995) equivalised household income quintile boundaries for the HEEP houses are given earlier. Analysis of the income data in relation to the 61 Māori HEEP households suggests Māori households are over-represented in the lower equivalised income quintiles and consequently under-represented in the upper income quintiles. Figure 81 shows the quintile for equivalised household income for the whole HEEP sample compared with households where one or more members of the households are Māori.

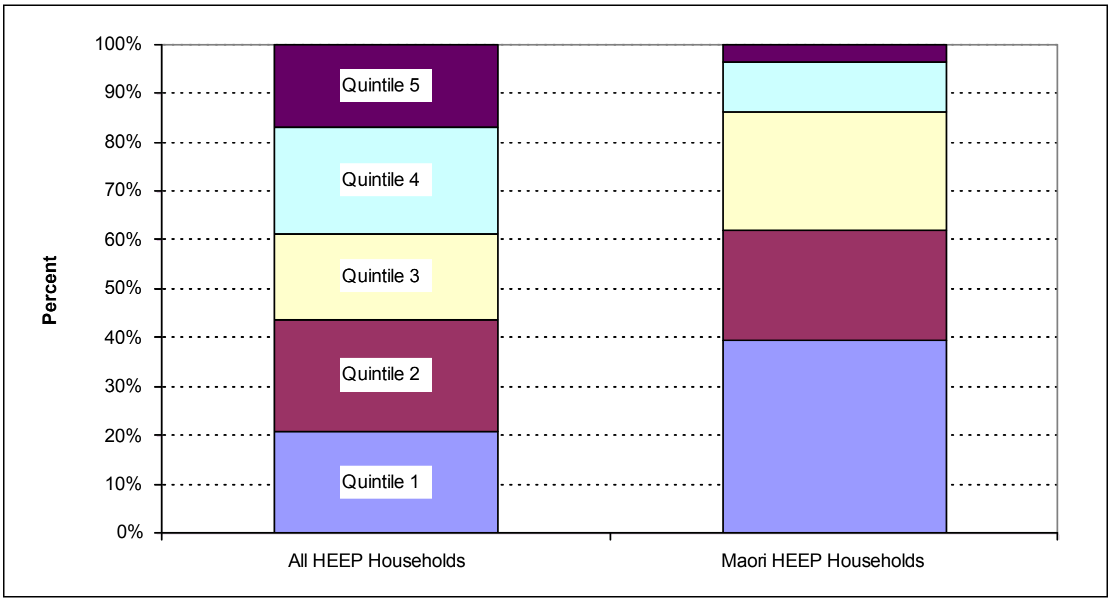

Figure 81: Equivalised household income – all & Māori HEEP households

Three bedroom houses are the most common house size among the 394 HEEP dwellings and also among the subset of Māori HEEP dwellings. However, on average, the Māori HEEP dwellings tend to be smaller than HEEP dwellings overall. The average floor area of the 394 HEEP dwellings is 121 m² compared to 106 m² for Māori HEEP dwellings. Moreover as Table 67 shows, despite having on average larger household sizes, Māori HEEP households tend to be clustered in dwellings with fewer bedrooms.

Size of house	Māori HEEP households*		All HEEP households^	
	N	%	n	%
<3 bedrooms	13	22.0	70	17.9
3 bedrooms	31	52.5	198	50.6
>3 bedrooms	15	25.4	123	31.5
Total	***59***	***99.9***	***391***	***100***

* Two missing cases ^ Three missing cases

Table 67: Number of bedrooms for Māori & all HEEP households

The majority of the 394 HEEP dwellings are over 25 years old. The Māori HEEP households tend to be over-represented among households living in pre-1978 dwellings (Table 68).

Age of house	Māori HEEP households*		All HEEP households^	
	n	%	n	%
Pre-1978	46	83.6	274	72.9
Post-1978	9	16.4	102	27.1
Total	***55***	***100***	***376***	***100***

* 6 missing cases ^ 18 missing cases

Table 68: Age of house for Māori & all HEEP households

Table 69 shows the majority of HEEP households have some level of ceiling or roof insulation, but Māori HEEP households are significantly over-represented among households that have none. Insulation, particularly in the ceiling or roof cavity, can result in increased indoor temperatures and more efficient use of energy. Thermal insulation has been mandatory in new houses since 1978 (Isaacs 1999).

All or part of roof insulated	Māori HEEP households*		All HEEP households^	
	n	%	n	%
Yes	36	62.1	296	80.0
No	22	37.9	74	20.0
Total	***58***	***100***	***370***	***100***

* 3 missing cases ^ 24 missing cases

Table 69: Roofing insulation status of house for Māori & all HEEP households

At 17.4°C the average evening winter living room temperature for Māori HEEP households is 0.4°C degrees cooler than the average for all HEEP households (17.8°C). Further analysis of evening temperatures confirms Māori HEEP households do tend to have a cooler evening living room temperature profile compared to HEEP households overall. Figure 82 shows the average winter (June to August) evening living room temperatures for all HEEP households and Māori HEEP households. The comparison of average temperature groupings in Figure 81 shows Māori HEEP households tend to be over-represented in average and colder-than-average households and under-represented among warmer-than-average households.

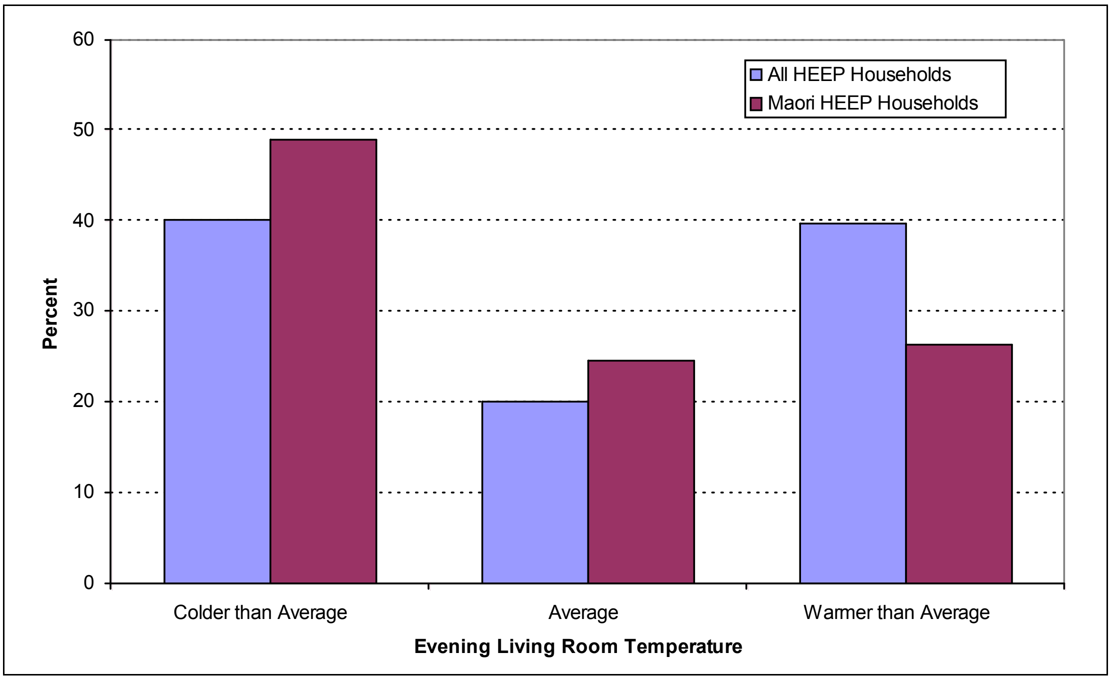

Figure 82: Winter evening living room temp – all & Māori HEEP households

When the ‘colder-than-average’ and ‘warmer-than-average’ dwellings are analysed, it is clear that ‘cold’ is the most common mean winter evening living room temperature category for Māori HEEP households (see Table 70).

Nearly half (49.2%) of Māori HEEP households have mean winter evening living room temperatures categorised as ‘below average’ or ‘cold’, compared with two-fifths of all HEEP households (40.2%).

Temperature Quintile	Māori HEEP households*		All HEEP households^	
	n	%	n	%
Warm	9	15.8	74	19.8
Above average	6	10.5	74	19.8
Average	14	24.6	75	20.1
Below average	12	21.1	76	20.4
Cold	16	28.1	74	19.8
Total	***57***	***100.1***	***373***	***99.9***

* 4 missing cases ^ 21 missing cases

Table 70: Winter evening living room temperatures for all & Māori HEEP households

Table 71 shows that there appears to be considerable variations in mean evening indoor winter temperatures by fuel type among the Māori HEEP households. Although the numbers of households are small, the mean winter living room temperatures for Māori HEEP households, particularly those heating predominantly with LPG or electricity, appear to be lower than for all HEEP households.

Fuel type	Māori HEEP households*		All HEEP households^	
	N	Temperature °C	n	Temperature °C
LPG	13	16.6°C	54	17.0°C
Electricity	16	16.5°C	114	17.2°C
Solid fuel	23	18.5°C	156	18.7°C

Table 71: Winter evening living room temp. by fuel for all & Māori HEEP households

Figure 83 shows there are no significant differences in the energy use profiles of Māori HEEP households as compared to all HEEP households.

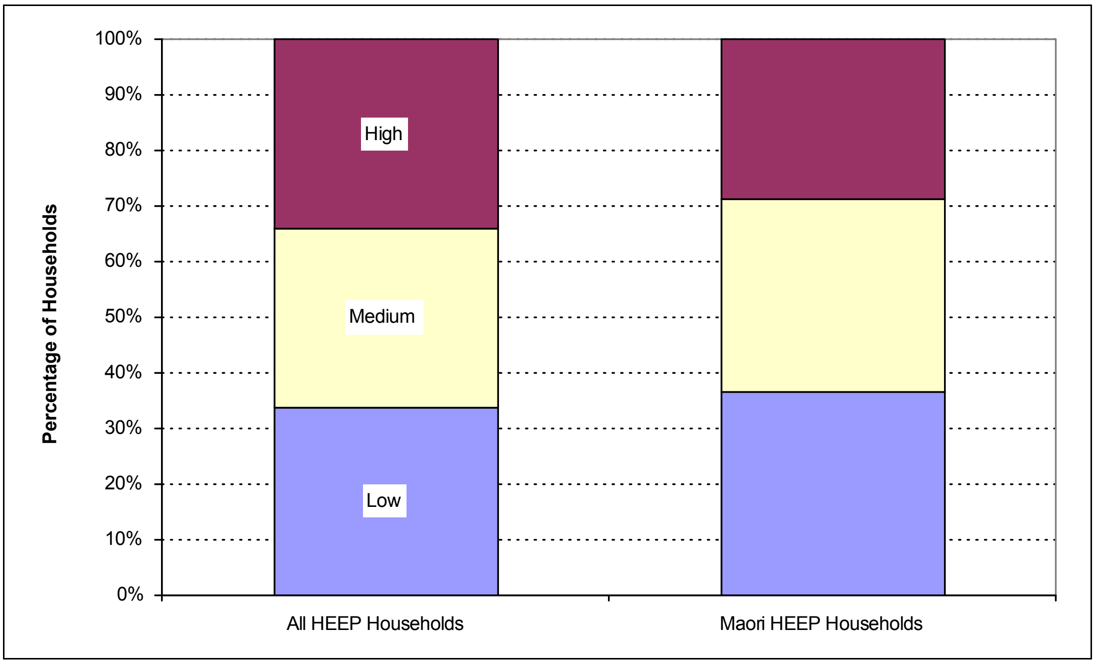

Figure 83: Total gross annualised energy use for all & Māori HEEP households

Although Māori HEEP households are slightly over-represented among low and medium energy households compared to all HEEP households, Figure 83 shows that overall the energy use profile for the Māori is broadly similar to that for all HEEP households. The mean annual gross energy use for all HEEP households is 11,223 kWh compared to 10,112 kWh for Māori HEEP households.

Figure 84 compares the heating energy use profile for all HEEP households with Māori HEEP households.

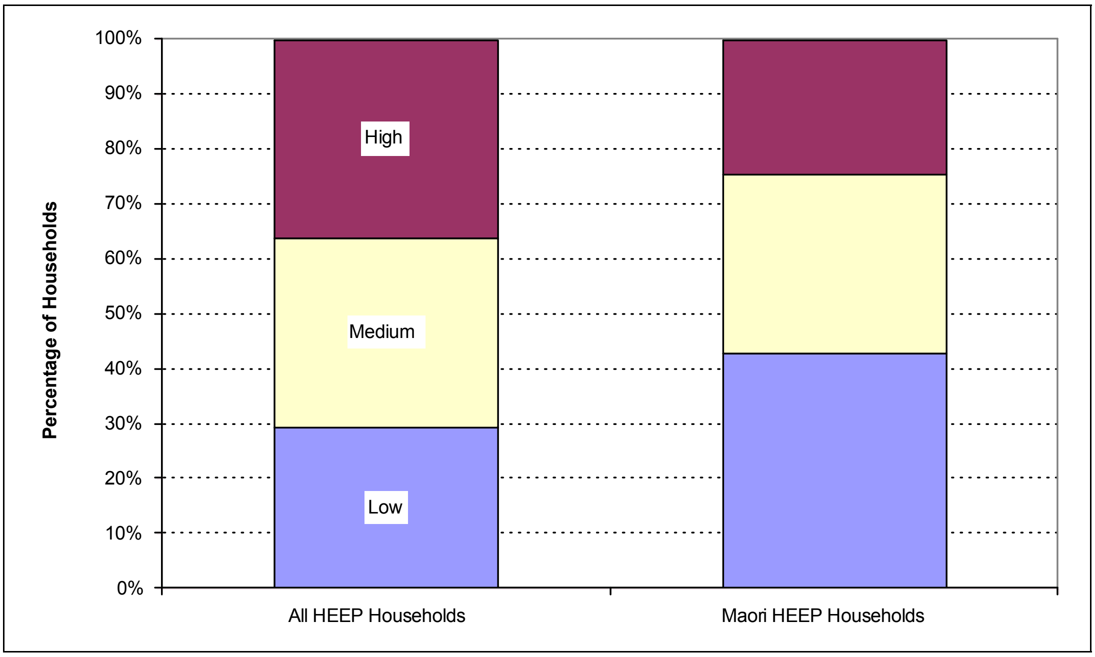

Figure 84: Total gross annualised heating energy use for all & Māori HEEP households

The mean annual gross heating energy use for all HEEP households is 3,827 kWh compared to 3,001 kWh for Māori HEEP households.

As Figure 84 shows, Māori HEEP households appear to be over-represented among low heating energy use households compared with all HEEP households.

Over two-fifths (42.9%) of Māori HEEP households are low heating energy use households compared with under one-third (29.4%) of all HEEP households.

Māori HEEP households are over-represented in the ‘cold’ winter evening living room category (Table 70). There are a range of negative health impacts associated with colder temperatures, as noted earlier. Condensation, damp and mould are associated with low temperatures. Damp and mould are associated with a range of illnesses including toxic reactions, allergies, inflammatory diseases, gastroenteritis and other infections (Bonnefoy et al 2004).

14.3 Impacts on Vulnerable Households of Moving Away from Solid Fuel

Historically New Zealand households have relied heavily on solid fuels to heat their homes. The increased availability of electricity and gas in the second half of the 20th century resulted in a shift away from reliance on solid fuel. However, solid fuels continue to be used for heating in a substantial proportion of households. Census 2001 figures show over two-fifths of households (45%) report using wood and about 9% of households report using coal (either solely or in combination with other fuels) to heat their home. The 2006 Census shows 40.9% of households report using wood and about 7.0% of households report using coal for heating (Statistics New Zealand, 2007).

Traditionally the use of solid fuel in residential homes has been identified as a major contributor to poor winter air quality. In locations in which the occurrence of visible winter smog is common (such as Christchurch or Nelson),[15] concerns about the polluting effects of solid fuel use have prompted programmes to shift users to other forms of heating, usually electricity based. In September 2005 National Environmental Standards for air quality in New Zealand came into effect. The national standards are aimed at reducing pollution and improving air quality by 2013.

This approach has been based on a number of assumptions, most importantly that solid fuel heating is:

- inefficient
- associated with poor temperature performance, and
- represents a heating mode of the past with its appeal and use in gradual but inevitable decline.

The evidence from HEEP, however, shows that the use of solid fuel is considerably more widespread than previously believed. Moreover, the indoor temperatures associated with solid fuel use in enclosed burners tend to be higher than those associated with other forms of fuel use. These findings raise both challenges and opportunities for all those concerned with energy use, the warmth of New Zealand dwellings, environmental protection and the health of New Zealanders.

Two tables have been prepared to compare the available historic data with the HEEP houses.[16]

- Table 72 compares the proportion of houses reporting the main fuel used for heating from the 1961 to 1971 Censuses and the HEEP houses. There was a jump of 28% in the proportion of houses using electricity from 10% in 1961 to 38% in 1965, but this remains reasonably stable for the 1971 Census and in the HEEP houses. The proportion of houses using mainly solid fuel (coal, coke or wood) fell by 34% from 83% in 1961 to 49% in 1966, but remained almost the same for the 1971 Census. Between 1971 and the HEEP survey, houses using solid fuel as their main heating fuel fell a further 40% to only 10% of the houses.
- Table 73 reports all the fuels used in houses – using the results from the *Survey of Household Electricity Consumption 1971-72* (NZ Department of Statistics 1973), the 1976 though to 2001 Censuses and HEEP. It is interesting to note that over the 30 year period covered by the four data sources, New Zealand homes have reported using on average 1.75 fuel types for space heating. Thus, it would appear that the majority of homes apply a distributed (heat) generation system by making use of more than a single heating fuel.

Table 72 shows that from 1961 to 1971, electricity was making a dramatic inroad into the use of solid fuel as the main means of heating – shifting from 10% to 42% in a decade. Table 72 shows that solid fuel was used in only 49% of dwellings in 1976 (whether as the principal or lesser importance heating fuel), compared to 83% reporting it as the main fuel in 1961. This is a major shift in fuel use, and at least in part reflects the promotion of electricity as a multi-purpose fuel.

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[15] See www.ecan.govt.nz/Our+Environment/Air/ or www.mfe.govt.nz/issues/air/programme/.

[16] For the purposes of this analysis, the reported fuel 'kerosene' has been taken as functionally equivalent to LPG – both are used in the main for portable space heating.

Main fuel used for heating	Census 1961	Census 1966	Census 1971	HEEP
Electricity	10%	38%	42%	43%
Gas	2%	1%	1%	16%
LPG*	2%	3%	6%	31%
Solid fuel^	83%	49%	50%	10%
Other	2%	6%	0%	
Not specified or no heating	1%	3%	1%	

Table 72: Main heating fuel – 1961 to 1971 Censuses & HEEP

*Assuming 'kerosene' in 1961, 1966 and 1971 Censuses is functionally equivalent to an LPG heater.
^ Assuming 'space heater' in 1961 and 1966 Censuses is an enclosed solid fuel burner.

The household data in Table 73 shows that solid fuel use increased between the 1976 and 1986 Censuses. Solid fuel use started to trend down to the 2001 Census where it was used in 54% of houses.

Fuel type used to heat dwelling	1971/72 Household Electricity Survey	1976 Census	1981 Census	1986 Census	1991 Census	1996 Census	2001 Census	HEEP
Electricity	92%	81%	72%	79%	77%	77%	72%	75%
Reticulated gas	5%	4%	5%	9%	16%	12%	13%	13%
LPG (or kerosene or oil)	15%	10%	7%			22%	28%	34%
Solid fuel	**59%**	**49%**	**51%**	**67%**	**60%**	**62%**	**54%**	**52%**
Other	1%	7%	4%	3%	2%	2%	2%	
No fuels used		1%	3%	1%	1%	2%	3%	
Average fuels per house	**1.73**	**1.51**	**1.40**	**1.57**	**1.56**	**1.75**	**1.70**	**1.74**

Table 73: Heating fuels – 1971/72 Electricity Survey, Censuses & HEEP

[1] Assuming 'kerosene' reported in the 1971/72 Survey, 1976 and 1981 Censuses is functionally equivalent to an LPG heater. Reticulated gas and LPG were not separately reported in 1986 and 1991.

About 59% of the HEEP households have a solid fuel appliance available for their use (Table 74).

Solid fuel appliance available	Self-reported data*		Monitored data	
	n	%	n	%
Yes	226	58	231	59
No	167	42	163	41
Total	***393***	***100***	***394***	***100***

* 1 missing case

Table 74: Availability of solid fuel appliances in HEEP households

The most commonly available solid fuel appliance is an enclosed wood/coal burner. About one-quarter of those households with the facility to use solid fuel have an open fire, but a significant number of those households with an open fire also have an enclosed wood burner (Table 75). Observed data includes the data from the occupant survey, house audit and monitoring. HEEP recorded all open fires in the house, whether they could be used or not. Many open fires are unusable, with cracks in the bricks, non-functional grates, or chimneys that have been blocked up.

Solid fuel appliance type	Observed data	
	n	%
Enclosed wood/coal burner	171	74
Open fire	40	17
Enclosed wood/coal burner and open fire	19	8
Total	***230***	***99***

*1 missing case

Table 75: Solid fuel appliance types in HEEP households (observed data)

There are statistically significant differences in the availability of solid fuel by region, north to south, climate zone and urban/rural environments. Table 76 shows HEEP households in Northland, Auckland and Wellington are least likely to have a solid fuel (SF) appliance available.

HEEP households with a solid fuel appliance – vocational variable	SF appliance available		SF appliance not available	
	n	%	n	%
Regional Council area				
Northland	15	50	15	50
Auckland	55	48	59	52
Waikato	35	65	19	35
Bay of Plenty	21	75	7	25
Gisborne/Hawkes Bay	17	63	10	37
Taranaki/Manawatu-Wanganui	9	90	1	10
Wellington	21	43	28	57
Nelson/Tasman/Marlborough	16	89	2	11
Canterbury	21	62	13	38
Otago/Southland	21	70	9	30
Total	***231***	***59***	***163***	***41***
North vs. South Island				
North Island	173	55	139	46
South Island	58	71	24	29
Total	***231***	***59***	***163***	***41***

Table 76: Availability of solid fuel appliances by location

Table 77 shows that households in warmer climates (NZS 4218:1996 Climate Zone 1) are least likely to have a solid fuel appliance available, while houses in cooler climates (Zones 2 and 3) have a very similar likelihood of having a solid fuel burner.[17]

HEEP households with a solid fuel appliance – NZS 4218 climate zone	SF appliance available		SF appliance not available	
	n	%	n	%
Climate Zone 1	75	49	78	51
Climate Zone 2	94	63	56	37
Climate Zone 3	62	68	29	32
Total	***231***	***59***	***163***	***41***

Table 77: Availability of solid fuel appliances by climate zone

Table 78 shows that households in rural areas are more likely than households in urban areas to have a solid fuel appliance.

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[17] NZS 4218:1996 *Energy efficiency – housing and small building envelope* is called as an Acceptable Solution to the NZ Building Code Clause H. Zone 1 is the upper North Island, Zone 2 is the lower North Island, and Zone 3 is the Central North Island plateau and the entire South Island.

HEEP households with a solid fuel appliance – urban vs. rural	SF appliance available		SF appliance not available	
	n	%	n	%
Urban	155	52	145	48
Rural	76	81	18	19
Total	***231***	***59***	***163***	***41***

Table 78: Availability of solid fuel appliances by urban/rural area

Two housing variables have a statistically significant association with the availability of a solid fuel appliance – the age of the house (Table 79) and the number of bedrooms in the house (Table 80). Table 79 shows older houses (pre-1978) are more likely to have a solid fuel appliance available. Table 80 shows that large houses are more likely to have a solid fuel appliance available. Dwellings with 1-2 bedrooms are least likely to have a solid fuel appliance available.

HEEP households with a solid fuel appliance – age of house	SF appliance available*		SF appliance not available^	
	n	%	n	%
Pre-1978	180	66	94	34
Post-1978	45	44	57	56
Total	***225***	***60***	***151***	***40***

* 1 missing case ^ 12 missing cases

Table 79: Availability of solid fuel appliances by age of house

HEEP households with a solid fuel appliance – size of house	SF appliance available*		SF appliance not available^	
	n	%	n	%
<3 bedrooms	33	47	37	53
3 bedrooms	114	58	84	42
>3 bedrooms	83	68	40	33
Total	***230***	***59***	***161***	***41***

* 1 missing case ^ 2 missing cases

Table 80: Availability of solid fuel appliances by size of house

One-person households are the least likely to have a solid fuel appliance available. Households with two or more members are over one-and-a-half times more likely to have a solid fuel appliance available than single-person households. As could be expected with the lower levels of solid fuel appliance available in single-person households, retired households are significantly less likely to have a solid fuel appliance compared to other life stages. Solid fuel appliances appear to be most common in school age households followed by working age households (Table 81).

HEEP households with a solid fuel appliance – life stage	SF appliance available		SF appliance not available*	
	n	%	n	%
Pre-school	34	57	26	43
School age	58	85	28	33
Working age	114	62	69	38
Retired	25	40	38	60
Total	***231***	***59***	***161***	***41***

* 2 missing cases

Table 81: Availability of solid fuel appliances by life stage

Households with one or more members in employment are more likely to have a solid fuel appliance available than households where all members are unemployed. Although equivalised income does not appear to have a significant association with the availability of solid fuel appliances in the HEEP households, analysis does show that solid fuel appliances are more likely to be available to the lowest household income quintile (Quintile 1) and the highest two quintiles. However, there is a different distribution of equivalised income quintiles for urban households compared with rural households, and for pre-1978 households compared to post-1978 households, which may explain any apparent differences in availability by equivalised income.

Table 82 shows open fires are much more likely to be available but not used more than enclosed wood/coal burners. Indeed, the majority of those with only an open fire did not use it for heating.

Solid fuel appliance type	**Appliance used***		**Appliance not used**		***Total***
	n	**%**	**n**	**%**	
Enclosed wood/coal burner	153	92	14	8	***167***
Open fire	18	47	20	53	***38***
Enclosed wood/coal burner and open fire	16	84	3	16	***19***

* 7 missing cases

Table 82: Solid fuel appliance type by use in HEEP households (observed data)

Of the 188 households using solid fuel, less than one-fifth (15.4%) rely solely on solid fuel to heat their home. As Table 83 shows, the majority use a combination of electricity/gas and solid fuel. Nearly one-fifth of solid fuel users also use LPG for heating. It is likely that in many cases electricity/gas and LPG heating appliances are being used to heat other zones of the house, such as bedrooms.

Fuel types used for heating	**SF appliance used***		**SF appliance not used^**	
	n	**%**	**n**	**%**
Electricity/gas and solid fuel	122	65	0	0.0
Electricity/gas, solid fuel and LPG	31	17	0	0.0
Solid fuel only	29	16	0	0.0
LPG and solid fuel	5	3	0	0.0
Electricity/gas only	0	0.0	31	89
Electricity/gas and LPG	0	0.0	3	9
LPG only	0	0.0	1	3
Total	***187***	***101***	***35***	***101***

* 1 missing case ^ 2 missing cases

Table 83: Use of solid fuel appliances by mix of heating fuels for HEEP households with a solid fuel appliance

Table 84 shows that the vast majority of HEEP households (98%) reporting use of a solid fuel appliance also report that its use involves multi-space/room heating including heating the living, lounge and dining areas of their house.

Area heated	**n**	%
Living rooms only	75	38
Whole house/all areas	63	32
Living rooms and service areas	38	19
Living rooms and bedrooms	17	9
Bedrooms only	2	1
Service rooms only	2	1
	197	***100***

* 3 missing cases

Table 84: House areas heated by solid fuel appliances for HEEP households using a solid fuel appliance (self-reported data)

While 63 households (nearly one-third) self-report that use of their solid fuel appliance heats the whole house, of the households monitored only 29 appear to be relying solely on solid fuel for their heating. This may indicate a high proportion of other heating being used for task-specific heating such as studying or workroom heating or for spot heating. Or it could indicate that despite a perception among respondents that solid fuel heating raises the temperature throughout their whole house, this is not always warm enough for comfort in all areas.

Analysis undertaken for the Year 8 Report (Isaacs et al 2004) highlighted significant differences in evening indoor temperatures, depending on the main fuel type used for heating. That analysis, updated in Table 85, shows houses heated with gas or solid fuel tend to be significantly warmer than electric and LPG-heated houses (using Kruskal-Wallis, X^2 = 35.6 on 3 DF, p <0.0001).

Fuel type	**Number of households**	**Temperature °C**	**Standard Error of the mean**
LPG	54	17.0	0.2
Electricity	114	17.2	0.2
Gas	36	18.1	0.4
Solid fuel	156	18.7	0.2

Table 85: Winter evening living room temperatures by heating fuel type for most used heating appliances

The earlier analysis also indicated significant variations in achieved evening indoor temperatures for different types of heating appliances. In relation to solid fuel, analysis shows the type of solid fuel appliance used results in clear differences in average evening indoor temperatures. As Table 86 shows, households using open fires tend to have evening living room mean temperatures lower than homes heated with an enclosed solid fuel burner. The evening winter living room mean temperature for households using an enclosed solid fuel burner is 18.8°C, compared with households using an open fire (15.9°C) and those using both an enclosed wood/coal burner and/or an open fire (16.4°C). These differences are statistically significant (using Kruskal-Wallis, X^2 = 31.8 on 2 DF, p <0.0001).

Solid fuel appliance type	**Number of households***	**Temperature °C**	**Standard Error of the mean**
Enclosed wood/coal burner	153	18.8	0.2
Open fire	18	15.9	0.4
Enclosed wood/coal burner and open fire	15	16.4	0.6

* 1 missing case

Table 86: Winter evening living room temperatures by available solid fuel appliance type for households using solid fuel

With the exception of open fires, analysis of HEEP data suggests that over all, homes using solid fuel burners tend to be warmer than those using other types of heating appliances. Although further analysis may be required, this appears to be true regardless of the thermal performance of the building (evening winter living room temperatures for HEEP post-1978 houses are on average 1.0°C warmer than pre-1978 houses). Households using enclosed solid fuel burners tend to be warmer than average, regardless of house age.

14.4 Energy and social policy – a critical interface

There are two examples in New Zealand of programmes in which social policy and energy policy are actively connected. The first is the retrofit insulation program partially subsidised by central Government through the Energy Efficiency and Conservation Authority (EECA) which in some regions use the Community Services Card as a targeting mechanism. The second is in the income support system in which beneficiary families facing extraordinary circumstances can apply for welfare assistance to meet household expenses. One of those household expenses is the cost of energy. These connections are largely the result of administrative convenience. They have not been in response to any real consideration of the interface between energy and social policy. Until very recently neither social policy outcomes nor the energy policy outcomes have incorporated mutually reinforcing success measures. Nor, indeed, had there been a critical analysis of the extent to which energy policy outcomes and social policy outcomes were consistent or in tension with each other.

Until HEEP, there were only indications that the pre-conditions at least existed for fuel poverty. Expenditure and consumption data showed inequalities in relation to fuel access between low income and high income groups, with low income groups tending to be exposed to expending higher proportions of their income on energy than high income groups. Similarly, within the beneficiary population the inability to cope with additional financial pressure associated with periodic increases in energy bills (either through price increases for electricity supply or unit price or consumption increases within the household) were typically cited as reasons for requiring additional benefit assistance or help from food banks. In addition, it was also clear that fire deaths, in rural areas at least, were associated with households using flame-based heating and lighting, either because they cannot bear the costs of reticulating electrical energy to a dwelling or because a household has not been able to maintain supply (CM Research 2000; Chalmers 2000; Duncanson et al. 2000; Duncanson et al. 2001; Duncanson et al. 2002).

The fragmentary nature of information around fuel poverty and other social dimensions of energy both reflected and sustained three key tendencies:

- First, because energy is a universally consumed good in which the market is the primary mechanism of distribution, there had been little analysis of the differential access of households to energy.
- Second, and connected to the first reason, social policy has had a history in New Zealand of being reduced to a focus on welfare policy. While there are strong connections between energy policy and welfare policy, they had been largely marginalised in the income adequacy debates which have seen adjustments in benefit levels as being the primary mechanisms to deal with deficient energy access among beneficiary households.
- Third, energy policy had been preoccupied by supply issues and management, rather than issues of demand and demand management or the issue of household access to energy and the implications for households of their energy consumption.

HEEP has shown that the connection between energy policy and social policy should not be ignored and that four questions need to be constantly at the forefront of policy in relation to energy. They are:

i. To what extent are well-being outcomes associated with differentials in access to and the efficient use of energy?

ii. What are the determinants of differential household energy use and energy efficiencies?
iii. To what extent can the nation’s ‘energy efficiency’ be increased and energy consumption minimised through the targeting of households with different socio-economic and demographic characteristics?
iv. To what extent can the optimisation of low income households’ incomes be pursued through energy efficiency?

15. HOT WATER HEATING, DWELLING SIZE AND SUSTAINABILITY

Patterns of energy use are changing in New Zealand. So too are households and the dwellings in which they live. This component of the analysis of social dynamics focuses on two changes and their likely impacts on resource use. The first is the emerging shift in hot water heating. The second is the increasing size of dwellings in the context of falling household size.

15.1 Hot water heating – the shift to gas

Nationally reticulated electricity was the bargain of the century for New Zealand householders. In 1988 households expended about 2.8 percent of the annual average wage on electricity consumption. This was not a great deal more, proportionately, than households spent in 1928, where the figure was 2.4 percent. However, the 1988 household was able to consume more than ten times the amount of energy – on average 8,500 kWh, compared to 760 kWh in 1928.

The profound shift to dependence on electricity of the 20th century is perhaps best represented by the increase in the number of consumers drawing electricity off the national grid. In 1918, supply authorities reported 50,400 consumers. By 1988, there were 1,492,380. In 1945, 92.7 percent of dwellings had an electricity supply, although the use of electricity was limited. For instance, only around a third of households used electricity for cooking. By 1968, 82 percent of dwellings used electricity for cooking, and 38.6 percent of dwellings were reported in the 1966 census as using electricity for space heating. By 1996 reticulated electricity had become the dominant energy source for three fundamental aspects of domestic life – cooking, water heating and space heating. The census for that year reported that in addition to over 95 percent of households using electricity for water heating, around 94 percent used electricity for cooking and 74.4 percent for space heating.

Despite this overwhelming take-up of reticulated electricity, its industrial production has created considerable resistance in the last 40 years from local communities. In 1973/4, proposals to raise the level of Lake Manapouri brought to an end the largely unhampered public works projects. Combined with the oil shocks of the mid-1970s, the spectre of energy shortages was raised. This was, and continues to be, exacerbated by periodic generation capacity crises when lake levels are low.

The fundamental ambivalence shown by New Zealanders towards electricity generation that impacts on wilderness areas, rivers and landscapes makes responding to increased electricity demand through generation inherently problematic. That ambivalence is one of the factors underpinning an evolving household and policy reorientation to alternative forms of energy. It is also a factor in the search for ways in which electricity might be produced through smaller scale generation and generation much closer to users. It is also one of the factors in the longstanding policy and household focus on energy conservation and, in particular, reducing the consumption of electricity within households.

Despite the still massive dominance of electrical hot water systems, New Zealand has recently seen the gas sector develop hot water options and a solar hot water industry becoming established. In addition, the development of low emission, efficient wood burning and pellet space heaters appears to be reviving an interest in wetback hot water heating. That shift to alternative, albeit embryonic, patterns of household hot water heating provides some opportunities to consider some new questions. In particular, whether such a shift will decrease electricity demand and relieve pressure on New Zealand's generating and distribution capacities. It also allows us to explore the broader impacts of such a shift on resource use and the wider range of environmental outcomes. It cannot be assumed that reduced electricity consumption is inevitably associated with reduced energy use. Nor can it be assumed that the consequences of such a shift will be uniformly beneficial.

15.1.1 Why focus on hot water?

Reducing hot water heating has long been the focus of household energy conservation strategies, for three reasons:

- Firstly, hot water heating has constituted a major proportion of household energy use. HEEP has shown that hot water heating on average constitutes 29 percent of household energy use (Figure 13) and 34 percent of household electricity use (Figure 6).
- Secondly, electricity is the primary source of hot water energy (Figure 126).
- Third, because of the dominance of electricity for heating hot water and the dominance of hot water storage cylinders, the reduction of hot water use and standing losses can have significant impacts on peak loads and on household costs.

However, the reduction of electricity use for hot water heating does not necessarily imply a reduction in energy use and this may have some profound implications in a policy environment in which sustainability can no longer simply be considered as a matter of reducing electricity consumption (Isaacs et.al., 2008)

Most New Zealand dwellings use electricity to heat their hot water. Of the 394 dwellings in HEEP, only 52 used gas for hot water heating but only 43 of these were entirely reliant on gas, and a further six used it as their main, but not exclusive form of hot water heating.

The HEEP data shows statistically significant associations between gas hot water heating and a dwelling's location in a rural or urban environment. The use of gas hot water heating is associated with urban localities. Rural dwellings, lacking mains gas, are more likely to use electricity-based systems, albeit often supplemented by wetbacks. There is also a statistically significant association between household income and use of alternative hot water heating systems. Households with higher equivalised incomes are more likely to have gas hot water heating systems.

Household or Dwelling Characteristics	**House uses gas**		**House does NOT use gas**	
	Number	**Percent**	**Number**	**Percent**
Urban/Rural				
Urban	46	93.9	254	73.6
Rural	3	6.1	91	26.4
Total	*49*	*100*	*345*	*100*
Equivalised income				
Quintile 1 (<= $15,653)	3	6.5	71	23.1
Quintile 2 ($15,654-$24,749)	9	19.6	72	23.5
Quintile 3 ($24,750-$35,000)	5	10.9	57	18.6
Quintile 4 ($35,001-$49,498)	14	30.4	63	20.5
Quintile 5 ($49,499+)	15	32.6	44	14.3
Total	*46*	*100*	*307*	*100*

Table 87: Gas Hot Water Heating, Location and Income Characteristics

Almost 94 percent of gas-using dwellings are located in cities, as shown in Table 87. Dwellings in rural areas and settlements made up 23.9 percent of the HEEP dwellings but 26.4 percent of the dwellings that did not use gas for hot water heating. Of the rural dwellings, only 3.2 percent used gas hot water heating while 15.3 percent of the urban dwellings did so. Table 87 also shows that equivalised income quintiles 4 and 5 have a considerably greater representation among gas hot water dwellings. Of the 74 households in the lowest quintile of equivalised incomes, only 4 percent use gas hot water heating. By comparison, a quarter of the households with incomes in the highest quintile use gas hot water heating.

Although not statistically significant, the proportion of one-person households in the dwellings using gas hot water heating is 10.2 percent, compared to one-person households making up 13.6 percent of houses using other forms of hot water heating (Table 88).

Household Characteristics	**House uses gas**		**House does NOT use gas**	
	Number	**Percent**	**Number**	**Percent**
Household Size				
1 person	5	10.2	47	13.6
2 people	12	24.5	132	38.3
3-4 people	24	49.0	124	35.9
>4 people	8	16.3	42	12.2
Total	*49*	*100*	*345*	*100*
Household Composition				
One family	35	71.4	276	80.5
Two or more families	2	4.1	7	2.0
Other multi-person	7	14.3	13	3.8
One person	5	10.2	47	13.7
Total	*49*	*100*	*343*	*100*
Tenure				
Owned	42	85.7	283	82.0
Not owned	7	14.3	62	18.0
Total	*49*	*100*	*345*	*100*
Life cycle				
Pre-school	8	16.3	52	15.2
School age	14	28.6	72	21.0
Working age	23	46.9	160	46.6
Retired	4	8.2	59	17.2
Total	*49*	*100*	*343*	*100*
House age				
Pre 1978	31	66.0	243	73.9
Post 1978	16	34.0	86	26.1
Total	*47*	*100*	*329*	*100*

Table 88: Gas Hot Water Heating, Household Size, Composition, Tenure and Life Stage Characteristics

Of the 52 one-person households in HEEP, only 9.6 percent live in dwellings with gas hot water heating, compared to 26.2 percent of households with three or more members. Similarly, households consisting of one family or one person tend to be under-represented among households with gas hot water heating. Households consisting of one or more families or composed of unrelated persons or a family and others tended to be over represented among households with gas hot water heating. Retired households are less likely to use gas hot water heating.

15.1.2 Using gas hot water is different

Electrical hot water systems and gas hot water systems perform differently (Table 89). Gas systems tend to be more highly powered, but they deliver lower temperature heated water and, in the case of instant gas systems, have no (gas) standing losses. Gas hot water use is associated with higher energy use than electrical hot water systems. That energy use, however, is not primarily in the form of mains power electricity.

All HEEP DHW for which data is available	Electric Storage[*]	Electric Night Rate	Natural Gas Storage	Natural Gas Instant
Number of houses in sample	346	16	27	16
Age (years)	19.6 ± 0.8	13.9 ± 2.3	12.2 ± 1.7	3.5 ± 0.5
Cylinder volume (l)	157 ± 2	214 ± 13	152 ± 8	107 ± 73
Element size (kW equivalent)	2.2 ± 0.05	2.5 ± 0.3	7.3 ± 0.2	23.7 ± 2.5
Thermostat setting (°C) (as read)	60 ± 0.5	63 ± 2	64 ± 2	47 ± 4
Measured tap temperature (°C)	63.2 ± 0.6	66.8 ± 2.4	59.2 ± 1.4	51.5 ± 2.9
Average cylinder temperature (°C)	61.3 ± 0.6	68.8 ± 2.4	57.6 ± 1.5	
Ambient temperature (°C)[+]	18.1 ± 0.2	19.6 ± 1.2	18.4 ± 0.7	19.6 ± 0.2
Standing loss (kWh/day)	2.4 ± 0.1	2.6 ± 0.3	4.2 ± 0.2	
Used hot water energy (kWh/day)	4.9 ± 0.2	4 ± 0.6	11.4 ± 1.2	8.8 ± 2.3

Table 89: Hot water cylinder characteristics by type of hot water heating

Notes: [*] includes electric systems with solid fuel, solar or other supplementary fuels
[+] estimated average temperature around the hot water cylinder

The use of gas for hot water does not reduce energy consumption. HEEP dwellings using gas hot water heating have average and median energy use patterns that are in excess of those dwellings that do not use gas water heating. This is the case for all end uses and for domestic hot water heating (Table 90).

Energy Consumption	House uses gas (n = 49)	House does NOT use gas (n=345)
Annualised gross energy (KWh per year) all fuels		
Minimum	5,620	2,698
Maximum	27,966	44,868
Mean	13,568	10,877
Median	13,038	9,717
Annualised gross energy (KWh per year) all fuels for DHW only		
Minimum	1,602	524
Maximum	9,796	14,671
Mean	5,113	3,042
Median	5,174	2,685

Table 90: Annualised Gross Energy Use and Annualised Gross Energy Use for Hot Water

Energy prices appear to have little moderating affect. It is of particular note that households with gas hot water are not simply enabled to use more energy while keeping their energy costs down. As Table 91 shows based on the then prices, the energy costs of households with gas hot water heating tend to be slightly higher than the energy costs of households without gas water heating.

Average Fuel Bill	House uses gas (n = 49)		House does NOT use gas (n=345)	
Summer				
Minimum	$40.00		$30.00	
Maximum	$270.00		$300.00	
Mean	$97.19		$93.67	
Median	$90.00		$85.00	
Winter				
Minimum	$50.00		$38.00	
Maximum	$400.00		$450.00	
Mean	$138.34		$123.83	
Median	$120.00		$120.00	
Winter fuel spend	**Houses**	**% of Houses**	**Houses**	**% of Houses**
Less than 10% of monthly income	32	100	239	92.3
More than 10% of monthly income	0	0	20	7.7
Total	*32*	*100*	*259*	*100*

Table 91: Average Summer and Winter Fuel Bills for all energy use

15.1.3 What about water use?

Just as higher energy use appears to be a characteristic of households in dwellings with gas hot water, there appear to be some indications that gas hot water heating may be associated with increased water consumption. HEEP did not monitor water use in dwellings but did collect data related to: the prevalence of low flow shower heads; water pressure; and water use patterns reported by the householders.

HEEP households using gas hot water systems are less likely to have low flow heads. That association is statistically significant. The lack of low flow shower heads in households with gas hot water heating is important because dwellings with gas hot water heating also tend to have higher water pressure (see Table 151). This is in contrast to most New Zealand houses, which have low pressure hot-water systems which tend to have lower flow rates. Mains pressure systems can produce warm water flow rates around double those of low pressure systems (see Table 163).

Also suggestive of increased water use among households with gas hot water heating are the showering patterns exhibited by those households. Table 92 shows that the average number of showers per week in dwellings with gas hot water heating was 20.7 compared to 17.8 per week in households not using gas for hot water heating. Households using gas hot water heating also show a higher median number of showers weekly – 17.7 compared to 15 in households not using gas hot water heating. The patterns are less distinct for bathing because of the relatively smaller number of baths taken over all households. It is, nevertheless, still apparent.

Differentials between dwellings with gas hot water heating and other dwellings are still apparent at each level of occupancy (Table 93). That is, somewhat higher water use patterns are apparent among households in dwellings with gas hot water compared to households of equivalent size with no gas hot water.

Shower and Bath Patterns	House uses gas (n = 49)	House does NOT use gas (n=345)
Total number of showers per week for whole household		
Minimum	2.0	0.0
Maximum	50.0	94.0
Mean	20.7	17.8
Median	17.7	15.0
Total household bath fills per week		
Minimum	0.0	0.0
Maximum	28.0	42.0
Mean	2.9	2.1
Median	0.5	0.0

Table 92: Key Water Use Patterns

Showers Weekly	Gas Hot Water Heating			No Gas Hot Water Heating		
	Household Size			Household Size		
	1 person	*2-3 people*	*4+ people*	*1 person*	*2-3 people*	*4+ people*
Minimum	4.0	2.0	6.0	2.0	0	7.0
Maximum	10.0	34.0	50.0	14.0	42.0	94.0
Mean	6.4	16.5	29.0	6.3	15.6	28.0
Median	7.0	14.0	31.5	7.0	14.0	26.0

Table 93: Number of Showers by Household Size by Type of Hot Water Heating

One explanation for the higher profile of showering among households in dwellings with gas hot water systems could be that gas, instantaneous gas in particular, means that households do not run out of hot water as can happen in electric hot water systems.

It is noted that, electric hot water cylinders have shown an increase in size over time (See Section 24.9.3). The trend towards large hot water cylinders has been accompanied by a trend towards smaller households. In 1971 the average household size was 3.38 people. This had decreased to 3 people in 1981, and by 2001, household size was 2.6 people. The average household size is forecast to fall further to 2.4 people by 2021. While the increasing capacity of electric hot water cylinders in new houses will provide improved service for the occupants, the issue of adequate hot water supplies in older houses continues as an issue to be resolved, particularly with the dangerously high water temperatures often found (Section 24.12.4).

There are two other alternative explanations that can be considered to the greater use of hot water in houses with gas systems, although they cannot be tested by reference to the HEEP data itself. One explanation lies in the characteristics of the households that tend to be found in dwellings with gas hot water heating[18]. It has already been noted that while HEEP did not find statistically significant differences in household composition profile of those living in dwellings with gas hot water heating compared to households in other dwellings, there are some indications that there are emergent socio-demographic differences between the two sets of households. Both multi-family households and households composed of non-family members or a mix of non-family members and related members have a greater representation in dwellings with gas hot water heating than in other dwellings. This may have impacts on consumption patterns within households.

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[18] See Section 24.6.5 for a statistical analysis of the differences in hot water energy use between gas and electric DHW households

A number of sociological studies have shown that families manage the distribution of resources and consumption patterns across family members (Cheal, D., 2003; Pahl, J., 1989). There is less research into the allocation of household resources across members of households in which there are multiple families or unrelated others. Despite anxieties about family changes and family breakdown, there are well-established social norms, values and roles that govern family life, interactions and resource consumption. Indeed some of those are codified in policy and statute. By comparison, the expectations, hierarchies of authority and reciprocities associated with membership of a household of unrelated others remain fluid and largely unregulated. Under those conditions, it is conceivable that the practices of rationing resources such as hot water, access to showers and other amenities are less well established and/or less stringent than familial households. The consumption patterns in the latter households may be more akin to the aggregation of one-person households than familial households of similar size.

The other explanation perhaps lies in the relative certainty that householders feel that they have over gas supply and use relative to electricity supply for electric hot water. One of the distinct differences between gas and electric hot water is that the latter tend to draw on a reticulated supply while gas reticulation is relatively limited. Bottled gas provides an alternative method of supply.

The connection of hot water cylinders to reticulated electricity comes, for householders, with a catch. Since the 1920s, electric hot water cylinders have been installed with various means by which suppliers could manage peak loads. Thus, the availability of hot water in New Zealand households has been determined for many decades not simply by the size of the cylinder, or the temperature at which the thermostat is set, or the consumption of hot water by household members, but by centrally managed supply outside the dwelling. That management could not, by definition, respond to the specific needs, tastes, or patterns of an individual household. Consequently some households in New Zealand have found themselves persistently at odds with the ‘ripple control’. At times of ‘energy crisis’, when low lake levels compromised generation by New Zealand’s hydro-stations, the number of households for whom electric hot water cylinders under-deliver increases considerably. Historically, other households, for instance those in Ngaio and Khandallah up until the 1960s, found themselves without hot water because water heaters were being turned off when they should not have been. The cause of these apparently random switch offs was found to be electrical pulses being sent out by Wellington’s commuter rail units (Rennie, 1989).

Essentially, then, electric hot water cylinders may well under-deliver to households irrespective of the size of the cylinder. But it is also possible that even where cylinders do not, users of gas hot water feel liberated from the constraints of central control. Taking advantage of that larger supply of hot water, the sense of independence and personal determination may raise the levels of consumption. It is notable that in-depth interviews with a small number of householders that had installed solar water heating as part of a retrofit programme also reported that they used hot water more frequently. Even those who recognised that the payback period from reduced energy expenditure was quite long reported that they valued the freedom solar energy gave them in relation to hot water use (Saville-Smith, K., 2008).

15.2 House size, energy use and sustainability

In 1971 the average household size was 3.38 people. Occupancy had decreased to 3 people in 1981 and by 2001; household size was about 2.6 people. The 2006 census shows that household size has stabilised somewhat. Nevertheless, the average household size is forecast to fall to 2.4 people by 2021 (Statistics New Zealand, 2005). Falling occupancy reflects a shift in household structure which is again forecasted to be a long term trend. Over the last decade the proportion of one-person households has increased from 20.7 percent in

1996 to 23 percent in 2006. In 1996, 256,569 dwellings had only one person living in them. Ten years later a further 71,730 dwellings were found to occupied by only one person.

According to Statistics New Zealand's family and household projections, by 2021 there are likely to be almost half a million dwellings occupied by one person only. That is, one person households in 2021 are expected to make up 26 percent of all households – an increase from 2001 of 48 percent (Statistics New Zealand, 2005). Even the 2006 census found, as did the two census counts before it, the most common household consisted of two people – usually couples.

Falling household size is not matched by falling dwelling size. The 2006 census makes this very evident. Table 94 sets out the number of bedrooms and rooms found in New Zealand's occupied dwellings in 2006. The three-bedroom home is still most common in the New Zealand housing stock. This is little different from the previous two census counts. In 2001, 47.5 percent of the private occupied housing stock consisted of dwellings of three bedrooms and three-bedroom dwellings made up 47.9 percent of the private, occupied stock in 1996.

Number	**% of Dwellings – Bedrooms**	**% of Dwellings – Rooms**
One	5.8	0.7
Two	19.8	1.8
Three	46.3	5.3
Four	21.6	9.8
Five	5.0	17.4
Six	1.0	25.7
Seven	0.2	16.9
Eight or more	0.3	22.4
Total	*100.0*	*100.0*

Table 94: Bedrooms and Rooms in Private Occupied Dwellings – 2006 Census

With falling household sizes, one might have expected an increase in the proportion of stock with fewer bedrooms and fewer rooms. This has not, however, been the case. In 1996, 76.7 percent of occupied dwellings consisted of dwellings with three or less bedrooms. By 2006, that proportion had fallen to 71.9 percent. Indeed, there has been a distinct increase in the proportion of the stock with four or more bedrooms. In 1996 only 22.3 percent of the occupied stock had four or more bedrooms. By 2006, that proportion had increased to 27.6 percent.

Similar trends can be found in relation to the total number of rooms in occupied dwellings. The proportion of dwellings that have eight or more rooms has increased from 15 percent of private occupied dwellings in 1996 to almost a fifth of dwellings in 2006. The consequence is that the proportion of smaller households living in larger dwellings has increased. Almost a quarter (24.1 percent) of households with one, two or three household members lived in dwellings with seven or more rooms in 2006. By way of contrast, only 18.4 percent of smaller households lived in these larger dwellings in 1996.

The census data on dwelling size, such as the number of rooms or bedrooms, tend to understate the strength of this 'sizing-up' trend simply because the stock increase over an inter-censual period is relatively small. However, the new stock added each year to New Zealand's existing stock has larger and larger floor-plates. The average size of a new house 25 years ago is just over half the average size of houses built in the ten months from April 2007 to January 2008. In 1973, the average house size was little under 110 sq metres, compared to 197 sq metres for the ten months to January 2008. Declining household size and increasing dwelling size means that an individual had an average of 32.5 sq metres housing space in a new home in 1973 but by 2008 that average had increased to 73 sq metres. That is, 2.3 times average increase of per person space. This raises very real questions about the resource efficiency of the new housing stock.

15.2.1 The HEEP dwellings

The analysis presented in this discussion is based on 393 HEEP dwellings. The average size of these is 121.5 sq metres with a median of 110 sq metres. The smallest HEEP dwelling is 51 sq metres and the largest dwelling is 315 sq metres. In terms of personal space, the average space per person is 52 sq metres with a median of 46 sq metres. The smallest personal space is 10.2 sq metres and the maximum personal space is 178 sq metres. Table 95 sets out the proportions of HEEP dwellings falling into specified dwelling sizes.

Sq Metres	Number of Dwellings	% of Dwellings
100 sq metres or less	154	39.2
101-150 sq metres	152	38.7
151-200 sq metres	65	15.5
201 or more sq metres	22	5.6
Total	***393***	***100.0***

Table 95: The Size of HEEP Dwellings

Among the HEEP dwellings, larger ones tend to be occupied by larger households. The association between larger households and larger dwellings is statistically significant. However, just as in the national housing stock there is only a loose association between household size and dwelling size, this is also the case in the HEEP houses. Regression analysis shows that less than 1 percent of the variation in the floor area of the HEEP dwellings can be explained by the size of the households that occupy them. While 65.4 percent of 1-person households occupy dwellings of 100 sq metres or less, 2-3 person households are more likely to occupy very large houses than households with four or more people.

In the HEEP dwellings, lower income households tend to live in smaller dwellings. The lowest equivalised income quintile of HEEP households is considerably over-represented among houses of 100 sq metres or less. Of the 78 HEEP households that make up the lowest income quintile, data on house size is available for 74 of these – that is, 21 percent of the 352 households for which dwelling size and income data are available. Those low income households, however, make up 30.5 percent of the households occupying dwellings of 100 sq metres or less. Moreover, of the 74 lowest income quintile dwellings, over half (55 percent) are 100 sq metres or less.

By way of contrast, of the 59 dwellings in the highest equivalised income quintile for which data is available, only 27 percent lived in dwellings of 100 sq metres or less. Those HEEP households in the highest income quintile are over-represented among the households living in larger dwellings in excess of 150 sq metres. They make up 16.8 percent of the HEEP households for which there is income and dwelling size data but 30.8 percent of the households occupying dwellings in excess of 150 sq metres. Around 11 percent of the variance in floor area can be explained by equivalised income.

15.2.2 Energy costs and dwelling size

There is a statistically significant association between energy expenditure and dwelling size. Indeed, around 16.6 percent of the variance in winter energy expenditure is accounted for by a dwelling’s floor area. For the HEEP houses, the average winter energy expenditure in dwellings of 100 sq metres or less is around $107.23 per month. For a dwelling with a floor area in excess of 200 sq metres, however, the average monthly winter fuel expenditure is

$183.18. It is notable, however, that the highest expenditure of any dwelling was $450 per winter month by a dwelling with a floor area between 151 and 200 sq metres (Table 96).

Sq Metres	Mean $	Median $	Minimum $	Maximum $
100 sq metres or less	$107.23	$100.00	$38.00	$250.00
101-150 sq metres	$125.59	$120.00	$40.00	$320.00
151-200 sq metres	$158.40	$150.00	$50.00	$450.00
201 or more sq metres	$183.18	$160.00	$75.00	$400.00

Table 96: Estimated Typical Monthly Winter Energy Costs by the Size of HEEP Dwellings

This pattern of higher energy costs for larger dwellings is somewhat muted by the number of people living within the dwelling. Nevertheless, dwelling size still appears to be important, although the small numbers in each category means that this interpretation needs to be treated as somewhat speculative. However, it does seem that the impact of household size on energy costs is most evident in smaller dwellings. In HEEP dwellings of 100 sq metres or less the average winter monthly energy cost is $53.91 more for a household with four or more members than the average winter monthly energy cost for a one-person household. In the HEEP dwellings of 151-200 sq metres, however, the average winter monthly energy cost is only $18.55 more for a household with four or more members than a one-person household. In short, in small dwellings household size has a considerable impact while in larger dwellings the impact of household size is significantly smaller (Table 97).

Sq Metres	Household Size					
	1 person		2-3 people		4 or more people	
	Mean $	Median $	Mean $	Median $	Mean $	Median $
100 or less	$85.14	$75.00	$97.50	$95.00	$139.05	$130.00
101-150	$104.16	$105.00	$122.58	$120.00	$139.27	$140.00
151-200	$150.00	$150.00	$153.12	$150.00	$168.55	$152.50
201 or more	No data	No data	$168.33	$160.00	$250.00	$250.00

Table 97: Estimated Typical Monthly Winter Energy Costs by Dwelling and Household Size

15.2.3 Total energy use and dwelling size

Dwelling size does have an impact on total energy use. Around 13.1 percent of energy use variance can be explained in terms of floor size. The HEEP data suggests that the average total kWh for a dwelling of 100 sq metres or less is 9373 annually. The median is somewhat less at 8076 kWh annually. The average annual total energy consumption of a dwelling in excess of 200 sq metres, however, is 1.6 times more at 15,349 kWh. More importantly the minimum consumption of a HEEP dwelling in excess of 200 sq metres is over twice (2.2 times) the minimum consumption of a HEEP dwelling less than 100 sq metres (Table 98).

Sq Metres	Mean kWh	Median kWh	Minimum kWh	Maximum kWh
100 sq metres or less	9373	8076	2698	27585
101-150 sq metres	11467	10620	2889	44868
151-200 sq metres	13399	12147	4919	30968
201 or more sq metres	15349	13778	5782	28415

Table 98: Total Energy Annual Use by the Size of HEEP Dwellings

When HEEP households are categorised into ‘low’, ‘medium’ and ‘high’ energy users, small dwellings are over-represented in the low user category. Conversely, high energy users make up 70.6 percent of the households living in dwellings in excess of 200 sq metres despite high users constituting only 34.4 percent of the HEEP households (Figure 85).

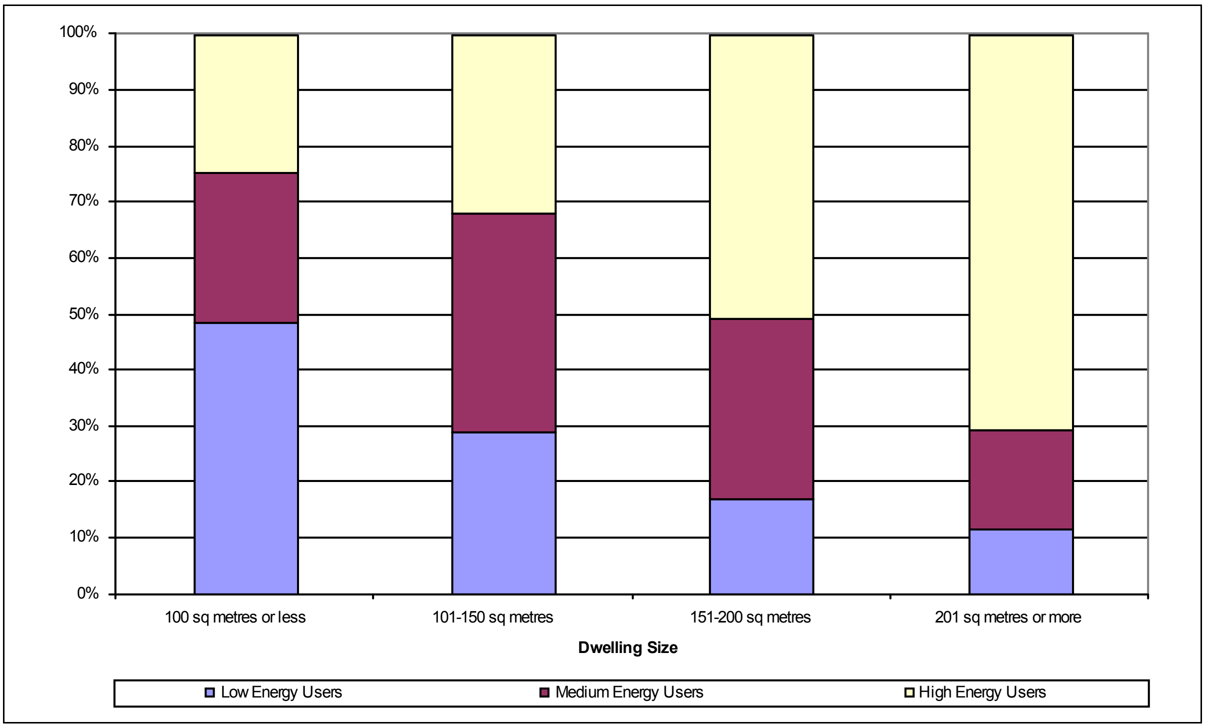

Figure 85: Energy Use Groups vs. Dwelling Size

There is higher energy consumption for domestic hot water among larger dwellings, reflecting the tendency for larger dwellings to use gas or to have multiple means of heating hot water. There is a statistically significant association between dwelling size and the main means used for domestic hot water. Of the HEEP dwellings less than 100 sq metres, 77.3 percent use electric domestic hot water systems – primarily hot water cylinders. Among the dwellings in excess of 150 sq metres, however, only 56.3 percent use electric systems as their main domestic hot water system. The tendency for larger dwellings to be over-represented among households using gas and/or multiple water heating systems is likely to have impacts on resource use beyond energy. There are indications that gas hot water heating may be associated with increased water consumption.

The potential of larger dwellings to use more water not only raises questions about the resource efficiency of those dwellings – particularly where occupancy and household size is low – but also has the potential to reduce the affordability of larger dwellings. While water charging is very limited in New Zealand, there is little doubt that water metering and charging are likely scenarios for the future as local authorities are confronted with the costs of extending water infrastructure.

15.2.4 Dwelling size, sustainability and affordability

Overseas, the trend to larger dwellings – referred variously to as *trophy houses*, *starter castles* or *McMansions* – has been identified as a trend antithetical to housing sustainability. The LEED tool promulgated by the United States Green Building Council, and other green building guidelines, tend to start with the premise that 'smaller is better' (Roberts, 2003). The HEEP data also demonstrates that larger dwelling size is associated with higher resource use. Irrespective of occupancy, larger HEEP dwellings show higher average and median levels of energy use (Table 99). The HEEP data also indicates that other resources such as water may also be characterised by higher patterns of consumption in larger dwellings.

Sq Metres	Household Size					
	1 person		2-3 people		4 or more people	
	Mean Annual kWh	Median Annual kWh	Mean Annual kWh	Median Annual kWh	Mean Annual kWh	Median Annual kWh
100 or less	5944	5652	8738	7640	11410	9792
101-150	7437	7252	11279	9632	13717	12857
151-200	10355	10355	12220	12067	17573	17542
201 or more	-	-	9092	8404	18326	18326

Table 99: Total Annual Energy Consumption by HEEP Dwelling and Household Size

From the perspective of social and economic sustainability, the size of a dwelling impacts significantly on affordability. Larger dwellings also cost more to acquire than smaller dwellings despite the per metre building cost being somewhat lower in larger dwellings. The report of the House Price Unit in the Department for Prime Minister and Cabinet (2008) suggests that the cost of a 145 sq metre new dwelling is in 2007 is around $247,636 while a 202 sq metre dwelling is $292,631. Under current conditions, a household taking up a 20 year mortgage would require a household income of over $118,000 to afford a new 202 sq metre dwelling. To buy a 145 sq metre dwelling at new building cost would require a household annual income of around $100,000. To buy a 100 sq metre dwelling at prevailing building cost would, however, require an annual household income somewhere in the region of $70,000.

The cost of dwelling acquisition, however, is only one aspect of affordability. Domestic operating costs are also important. One-person households in dwellings of 151-200 sq metres had twice the median winter monthly energy cost of dwellings 100 sq metres or less. Households with 2 or 3 household members in dwellings in excess of 200 sq metres had median monthly winter energy costs of around 1.7 times those of similar sized households in dwellings 100 sq metres or less.

The impacts of dwelling size, however, go beyond the entry affordability of housing or the affordability of domestic operating costs. The HEEP data need to be treated with caution, but it does indicate that there are very real potential costs associated with increased energy demand associated with larger dwellings. In the year ending March 2007, 25,740 residential building consents were approved with an average floor size of 194 sq metres. The average total energy use of HEEP dwellings between 151 and 200 sq metres is 13,399 kWh some 4,026 kWh above the average annual energy use of dwellings 100 sq metres and less and 1,932 KWh above the average annual energy use of HEEP dwellings between 101 sq metres and 150 sq metres.

The transformation of the housing stock from a stock dominated by larger rather than smaller dwellings will take time. But new stock is likely to be bigger. This is the international trend and there appears to be a strong perception among builders that they can achieve better returns from constructing larger and more expensive dwellings (DPMC, 2008). If this is the case, the issue of housing stock affordability and the problem of constraining resource demand are going to be very real challenges in the future.

16. MEASURING ENERGY USE IN WOOD AND SOLID FUEL HEATING

A method for in-situ monitoring of solid fuel burners has been developed that is cheap and easy to install and calibrate. This method was used to monitor 244 solid fuel burners in houses, estimating their heat output at 10 minute intervals. Nationwide solid fuel use was shown to be 20% of residential energy consumption, four times higher than the official statistics at the time, and is the dominant fuel source for space heating in New Zealand.

16.1 Introduction

Although there have been large reductions in wood and coal use due to air pollution concerns and by competition from other fuels, even in developed countries solid fuel is still a major source of heating. In some countries, wood (and more recently, processed wood such as wood pellets) is seen as an environmentally preferable fuel choice. New efficient wood burners have been developed while inefficient and polluting open fires have been largely phased out or banned altogether in many locations.

Despite the obvious importance of solid fuel as a domestic energy source, there has been little research into its energy use. Most research has been to gain information on the sources of air pollution and is largely restricted to surveys or interviews, or the monitoring of particulate and pollutant emissions. Such surveys can rely on the house occupants to estimate the use by volume or weight of wood – in terms of number of pieces or number of baskets, or quantity of wood acquired for the heating season.

In New Zealand, Lamb (2005) used written diaries for the house occupant to report the weight of wood or coal burned during a two week period in winter of houses in Christchurch. Wilton (2005) conducted a nationwide survey of solid fuel use, using a similar methodology. They both used Lamb's (2005) same fixed log and basket weights, which is questionable as the log and basket weights in Christchurch (one city) may not be the same as in other parts of New Zealand. Christchurch has a relatively cold climate, so if the log and basket weights are higher than average this might lead to an overestimate of national wood fuel use.

Whilst occupant self-reported wood use can give a rough estimate of the quantity of wood (provided the data collection is designed and implemented well), it is difficult to convert this to accurate estimates of space heating energy output for four main reasons: 1) The volumetric energy content of wood varies widely by species, and since most self-report studies use volume (e.g. a basket) the species needs to be known if accurate estimates are to be made. If the weight of wood is known, the net energy content per kg varies little between species for dry wood (Isaacs et al, 2005; sec 6.6). 2) The moisture content has a large effect on the net heat output and this is usually unknown, even if the wood is considered well seasoned. 3) The actual efficiencies of solid fuel burners in use will not always be the same as under laboratory conditions, particularly if the burner is run at low heat outputs, operated poorly, or has not been well maintained. 4) Some occupants do not provide reliable estimates of wood use. Together, these factors make the calculation of heat output from self-reported wood use highly inaccurate.

Measuring the energy input or output of a wood burning appliance in-situ is difficult and it appears that few researchers have attempted it. Modera and Sonderegger (1980) developed a method to measure the in-situ efficiency of fireplaces by maintaining constant temperatures with electric heating balancing fireplace heat output fluctuations, and monitoring air infiltration (natural and forced) and environmental parameters. A heat balance calculation was used to calculate the net efficiency of the fireplace (including infiltration losses forced by the fireplace), which ranged from 5.8% to 31.5%. The net efficiency of open fireplaces was found to be 5.8% to 6.6%, with higher efficiency for partially and fully enclosed fireboxes.

Modera, Wagner and Shelton (1984) developed a relatively simple method for monitoring the heat output of a stove using only one temperature sensor – either a radiometer or surface temperature. In this method the correlation between the stove temperature and the heat output was established, and this correlation predicted the heat output with an accuracy of about ±20% over the full range of the stove. The heat outputs were measured with the stove installed in a room-size calorimeter. Using this method in actual houses would mean relying either on a laboratory calibration of a similar unit, or on a calibration in the house, possibly using the techniques developed by Modera and Sonderegger (1980).

This method was further developed by Modera (1986) to be applicable for stove models that were not tested in the calorimeter. An equation using the stove surface area, ambient temperature, and one or more representative surface temperatures was derived to predict the heat output of the stove (Equation 16). Comparison with calorimeter measurements demonstrated that the method underestimated the heat output by on average 8%, and a variation between stoves of 15%, based on testing of four stoves.

This method and householder reporting was then used to monitor wood use in 100 homes in the Hood River Conservation Project (Tonn and White 1989). The average annual heat outputs were 6,680 kWh before and 4,820 kWh after retrofit. Comparison of the household reports of wood use and the monitored wood use indicated that the householder reporting was unreliable, with a poor correlation (~0.15) found between reported cords of wood used and energy output. This shows that self-reported wood use is an inaccurate way of estimating energy output, which matched our experience (Isaacs et al, 2005; sec 6.6).

Wood stove usage was monitored in the End-Use Load and Consumer Assessment Program (ELCAP), using thermocouples to determine if the stove was in use or not. Only the frequency of use was monitored, with no information recorded on the heat output (Pratt et al 1993).

16.2 Method

At the time of the HEEP pilot program (1995–1997) the various methods used by other researchers were investigated, but none offered a reasonably inexpensive, reliable and accurate method that could be quickly installed. Modera's (1986) method was tried, but this was unsuccessful as the calculated heat outputs apparently exceeded the calorific value of the wood used.

In some of the early HEEP pilot houses, Industrial Research Limited undertook in-situ efficiency calibrations on some burners (Stoecklein and Isaacs 1998). The house occupant was asked to keep a written record of the fuel use, which could then be used to calculate the heat output using the calibrated efficiency. Typical pieces of wood were weighed and designated as small, medium or large, and baskets of wood similarly weighed. A thermocouple data logger was also connected to the wood burner (usually in contact with the flue) to monitor the burner use. It was hoped that the wood burner temperature would relate to the wood use.

Unfortunately the method had many uncertainties that would not have been found in laboratory testing. The accuracy of the log books was not as high as hoped and the weight estimates were not helpful, and the wood species and moisture content was usually not known. This eventually became a semi-manual process, comparing logbooks with the monitoring. The results were not acceptable and the cost of the efficiency calibration was too high for large-scale use.

At the conclusion of the pilot program we did not have a suitable method for determining solid fuel energy use. It was decided to continue with log books and burner surface temperature monitoring in the hope that a suitable analysis method could be developed.

Several further attempts at analysis were made over the ensuing years, with none being fully successful (Stoecklein et al 2001). The final breakthrough came with the convergence of several other analyses in HEEP. The simple thermal model that was used previously was refined, and more experience gained in how to cope with poorly quantified loads such as solar gains. Good estimates of the unmonitored heating were therefore possible. The quality of the monitored data was also enhanced by an improved thermocouple and data logger calibration process, and data inspection.

16.2.1 Estimating unmonitored heat loads

The unmonitored heat loads were estimated by using the room or house as a calorimeter. If the U-value and thermal mass of the room are known, and the internal and external temperatures are measured, then the net energy input to the room or house can be estimated. By subtracting the monitored energy input, and making allowances for internal gains (e.g. hot water standing losses and metabolic gains), the difference at night time (i.e. no solar gains) can be attributed to the solid fuel burner.

The U-value and thermal mass were calculated by using ALF3 (Stoecklein and Bassett 1999). House plan details, construction type, climate, window and wall areas, and insulation levels were input into ALF3 which calculated an overall envelope loss including infiltration losses. Generally the whole house was used, as energy loads cannot normally be localised to specific rooms, although a smaller zone could be used for calibration e.g. top storey only. The internal temperature was usually a simple average of the two living room and one bedroom measurements. Where appropriate, a floor weighting was applied if the bedroom areas were much larger than the living room areas, but this was decided on a case-by-case basis and documented in the analysis.

The internal loads were usually calculated from the overall total load for the house (including gas and electricity) minus the hot water load. The internal load then had metabolic loads added (based on the occupants' age and sex, time spent in the house, and bedtimes), and hot water standing losses (if the cylinder is located within the thermal envelope). In some cases, other particular loads may have been removed from the whole house energy use e.g. garage or spa pool. Again, this was carried out on a case-by-case basis.

These parameters were then used to make estimates of the missing heat load using the STEM (Short Term Energy Monitoring) methodology (Shorrock, Henderson and Brown, 1991) which treats the house as a thermal circuit with one heat loss element and one heat storage element. The process is described in detail in (Stoecklein and Isaacs 1998) and Stoecklein et al (2001).

The STEM modelling equation (Equation 15) is:

$$q_{heat} = UA \cdot (T_{in} - T_{Out}) + mC_p \left(\frac{\partial T_{in}}{\partial t} \right) \qquad \textbf{15}$$

where:

q_{heat} = Heat delivered to house interior by internal gains and heating (W)
UA = Whole house heat loss coefficient (W/°C)
T_{in} = Interior air temperature (°C)
T_{out} = External air temperature (°C)
mC_p = Thermal mass of the house (Wh/°C)

$\frac{\partial T_{\text{in}}}{\partial t}$ = Rate of change of interior air temperature (°C/hr).

16.2.2 Accuracy of estimation of unmonitored heat loads

To estimate the accuracy of the calibration process, all the HEEP houses with large monitored heaters (e.g. natural gas heaters) were put through the same type of processing. The results for one house are shown in Figure 86. The top plot of the figure is from the 10 minute monitored data. It has a lot of scatter as the heater is controlled by switching on and off a large burner and the house also has a gas instant water heater, which when subtracted from the total gas use creates further scatter. To estimate the slope of missing heat load to measured heat load, the data are aggregated in 100 W bins as shown in the lower plot. The fitted line is from a least squares linear regression with each point weighted by the number of points in each bin, fitted to all the data points. The slope of this line is 0.85, so the missing heat load is 85% of the monitored heat load. The monitored heat load is a gross energy, and the net heat output of a gas heater would be 80–90% of that figure, so a slope of 0.85 is good. As the method works acceptably for the monitored heating fuels, it is reasonable to assume that it will work for unmonitored solid fuel load.

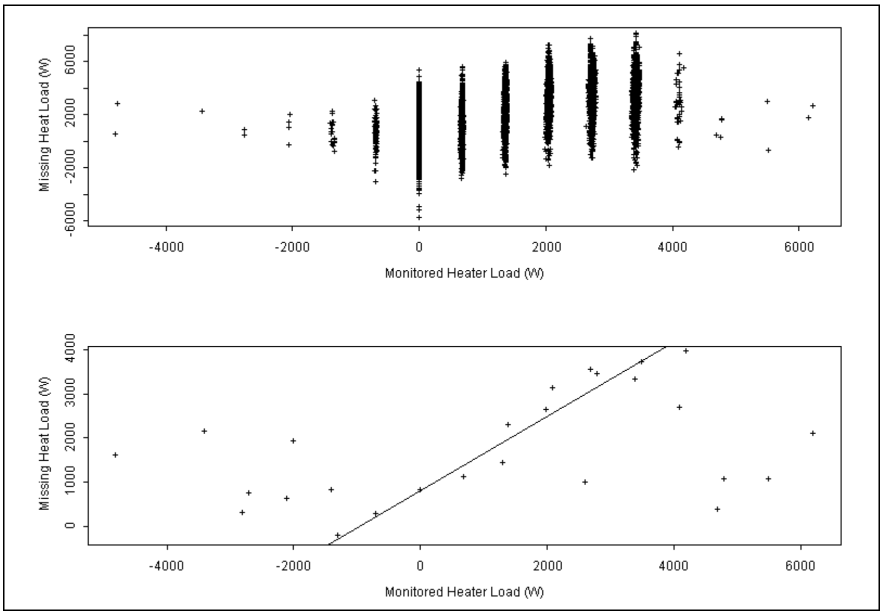

Figure 86: Test calibration of gas heated house – House 1.

This process was repeated for a number of other houses, and the results compared to estimate the accuracy of this process (see **Table 100**). If the calibration is accurate and the fuel has 100% conversion efficiency into heat in the house, the slope will be equal to 1.

House	Gas heater slope
1	0.85
10	0.67
11	0.64
12	0.72
13	0.81
14	0.43
17	0.52
19	1.13

Table 100: Calibration slopes

The average slope of the gas heaters is 0.72 ± 0.22, using the sample standard deviation (SD). The precise efficiency of these gas unit heaters is unknown, but likely to be around 80%. Assuming it is 80%, the average of the calibration slopes is 0.9 ± 0.1 (SD of the mean), which is not significantly different from 1. This demonstrates that there is not a large systematic bias caused by the calibration process. The standard error in the calibration for a single heater is ± 0.18 or ± 20%.

16.2.3 Calibration of solid fuel burners

The calibration data for the solid fuel burner from House 2 is presented as an example (Figure 87). A plot of the 10 minute solid fuel temperature shows the correlation with the missing load. Interestingly it is very close to linear, despite the theoretical fourth order dependence of radiant heat output on temperature. This may be due to the relatively small range of absolute temperature (from about 350K to 600K), and the fact that the thermocouple measures flue temperature which may not be in a direct relationship to the firebox temperature, or to the convective heat output of the burner. A few solid fuel burners do show some curvature, and for these a second order polynomial was fitted.

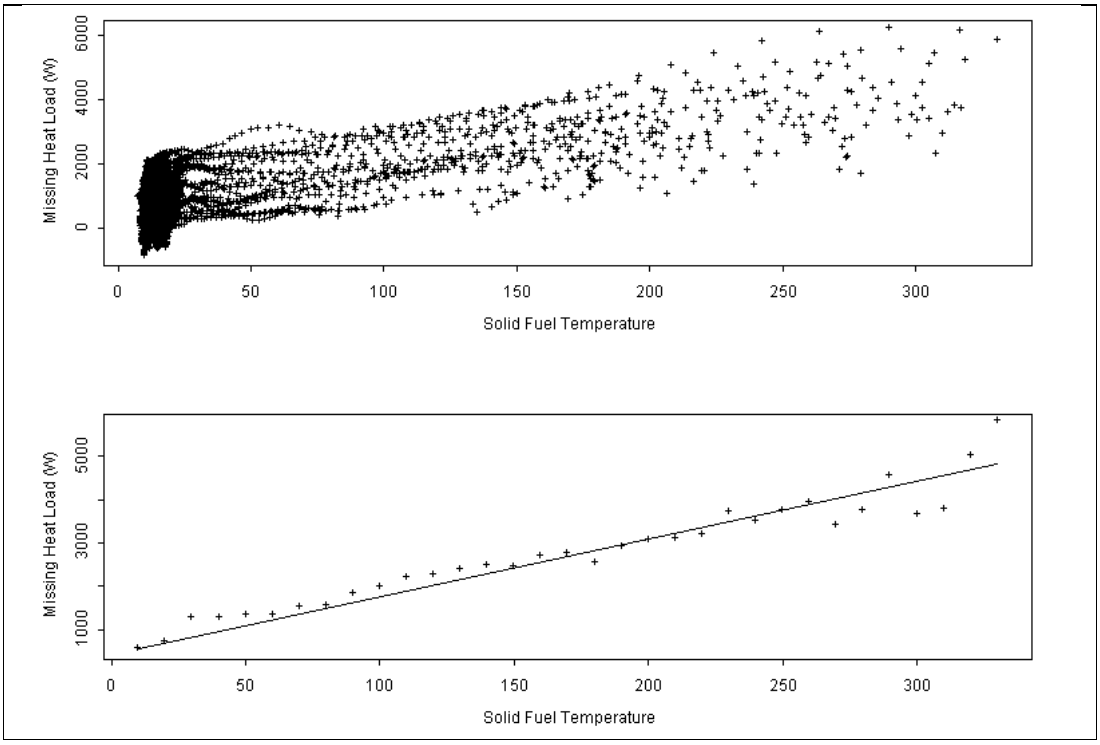

Figure 87: Solid fuel calibration graphs (House 2)

The solid fuel calibration slope was taken from a weighted linear regression fit of the data grouped according to the solid fuel temperatures in 10°C bins, using only data from 50°C and above. The intercept was then adjusted so that the output of the solid fuel burner is 0 W at 17.5°C – a typical average indoor ambient temperature during winter heating periods. For the example in Figure 87 the parameters were
92.1+11.0×Monitored Temperature. For this burner, the maximum 10 minute average heat output was about 3.5 kW.

16.2.4 Net to gross conversion efficiencies

HEEP uses gross energy data, so the net energy output estimates need to be converted. Table 101 gives the assumed conversion efficiencies (Isaacs et al 2006):

Type	Efficiency (%)
Open fire	15
Pot belly	35
Enclosed burner	60

Table 101: Assumed efficiencies of solid fuel burners

Efficiencies of modern enclosed burners are often tested at 60–70% or higher. The average label efficiency of the HEEP monitored wood burners was 63% on low, 68% on medium, and 64% on high. The average space heating efficiency of solid fuel burners approved by Nelson City Council is 71%[19]. Since most solid fuel burners in HEEP are not the new, clean air-approved types, the low efficiency setting of the basic type was used, and de-rated slightly to 60% to reflect lower efficiency in use at low heat outputs.

16.2.5 Difficult houses

As is usual with field experiments, some difficulties were encountered. A few houses give a very poor correlation between the solid fuel temperature and the missing load calculated for the whole house. This can be due to the other energy uses in the house being large compared to those in the room with the solid fuel burner. The way to solve this problem is to use the room that the solid fuel burner is located in, rather than the entire house, and to only include metered loads that are known to be released in this room. This in effect uses one room as a calorimeter, rather than the whole house. In most instances a satisfactory calibration could then be performed.

16.3 Comparison with Modera's Equation

For a selection of solid fuel burners the calculations using the equation of Modera (1986) (Equation 16) were compared to the outputs calculated using the HEEP method:

$$Q = A_s \left\{ \varepsilon_s \sigma \left(T_s^4 - T_a^4 \right) + K' \frac{\left(T_s - T_a \right)^{4/3}}{\left[\left(T_s + T_a \right)/2 \right]^{0.41}} \right\}$$

Equation 16

Where:

Q = Total heat flow from the surface (W)

σ = Stefan-Boltzmann constant, 5.67×10^{-8} W/m²K^4

A_s = Surface area of the burner (m²)

ε_s = Emittance of surface

T_s = Absolute temperature of surface (K)

T_a = Absolute temperature of ambient surroundings (K)

K' = Dimensional constant: value = 15.9 W/m²K$^{0.92}$

This equation, when plotted with typical values for the temperatures and a realistic emissivity of 0.8, gives the plot of heat output per m² versus temperature in Figure 88. This plot has pronounced curvature, which was not seen in most of the HEEP calibration curves. Only 20% of the HEEP calibration curves were fitted with second order polynomials, usually with only modest curvature, and 80% using the heat output as a linear function of the temperature.

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[19] www.nelsoncitycouncil.co.nz/environment/air_quality/burners_approved_table.htm

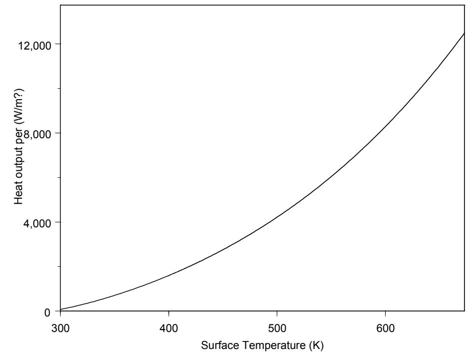

Figure 88: Equation 15 heat output

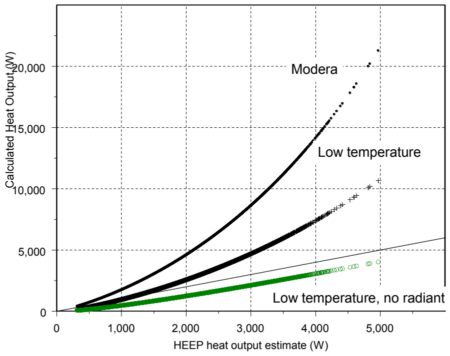

Figure 89: HEEP estimates and Equation 15

A variety of HEEP solid fuel burner heat outputs were compared to the method of Modera (1986). In general, Modera's method gave an overestimate of the heat output, with larger overestimates for larger heat outputs due to the non-linear heat output. A typical example is given in Figure 89. HEEP usually monitored flue temperatures, which are usually lower than firebox surface temperatures, so the actual estimates using Equation 15 should be even higher. Several adjustments were made to try to reconcile the estimates. Reducing the solid fuel burner flue temperature for calculation (as a set fraction of the difference between ambient and flue temperatures) reduced the difference between the two methods (Figure 89 'Low Temperature' points). At a value of about 0.7 times the (flue – ambient) temperature the curvature was reduced somewhat, and the overall average heat output was much closer. Removing the radiant heat term reduces the curvature, however the heat output then becomes an underestimate (Figure 89 'Low Temperature, no radiant' points).

The difference seems likely to be due to the typical solid fuel burner in HEEP and the types of stoves used by Modera (1986). The stove types used by Modera (1986) assumed that the stove was a simple firebox with the firebox as the main radiant and convective heating surface. Most of the solid fuel burners found in HEEP are double burners, which use an efficient double burning combustion process that may lead to a larger variation of temperatures between surfaces than a single burning process. The ceramic lined firebox is also surrounded by a separate steel box separated by an air cavity. This traps some of the radiant heat in the cavity, giving a lower surface temperature to the exterior, which is safer for people and for fire risk, and allows smaller clearances to combustible materials and acts as a convective cavity. Most enclosed wood burners also have a window which radiates some heat directly. These differences may mean that the assumption of Modera (1986) that a single temperature can be used to characterise the burner surface is invalid and a more complex model may be required.

It appears that the HEEP solid fuel burners are, in general, producing a larger fraction of their heat output as convective heat than the wood stoves used by Modera (1986) and with a lower radiant external surface temperature. Using a lower surface temperature in Equation 15 in some way compensates. However, the actual physics of the heat transfer process may not be described properly by this equation.

16.4 Results

The average annual energy consumption of HEEP houses that use an enclosed solid fuel burner was 4,500 kWh. Some houses have more than one solid fuel burner but generally the second one (often an open fire) is used infrequently. Open fires may have very high gross energy consumption as their efficiency is very low (see Table 101).

Type	Energy per appliance (kWh)	SE	Energy per house (all houses) (kWh)	SE
Open fire	995	285	100	36
Enclosed burner	4,480	415	2,075	256

Table 102: Annual gross energy input by appliance type

There are major differences in energy consumption by region, as shown in Table 103. The warm and cool clusters are small towns and rural areas, split at 900 heating degree days base 15°C, and together represent roughly half of New Zealand households. Energy consumption of solid fuel is much higher in colder climates, as solid fuel burners are both more common and more intensively used.

The average energy consumption of solid fuel for all houses is 2,150 kWh ± 250 kWh per year. This is about 20% of all domestic energy consumption (electricity, gas, LPG, and solid fuel). The Energy Data File *Energy Supply and Demand Balance June Year 2004* (MED 2005) estimated solid fuel use (coal + wood = 2.9 PJ) at 5% of energy consumption in domestic buildings. The HEEP results have been used to update these national statistics so solid fuel is now 14% of domestic energy use (MED 2006; Isaacs et al 2006). More than half of all New Zealand residential space heating is from solid fuel.

Location	Heating degree days, base 15°C	Energy per household (kWh)	SE	Energy per household using solid fuel (kWh)	SE
Auckland	670	810	230	2,690	650
Hamilton/Tauranga	930	1,160	440	2,740	860
Wellington	1,120	240	100	850	290
Christchurch	1,470	1,220	390	2,440	670
Dunedin/Invercargill	1,730	1,870	630	3,740	940
Warm cluster	670	1,830	290	3,520	440
Cool cluster	1,240	3,980	710	5,320	880

Table 103: Variation of gross annual solid fuel energy consumption by location

Roughly 5% of the total amount of solid fuel consumed is used in open fires, which are very inefficient and much more polluting than enclosed wood burners. However, a high proportion of open fires are not used, or used only a few times per year.

An enclosed wood burner can put out large amounts of heat, typically around 15 kW for a mid-sized burner. However, the HEEP monitored heat outputs are much lower – typically in the 0.5 to 4 kW range and two-thirds of enclosed solid fuel burners never exceeded a 10 minute averaged 4 kW output. This is lower than the rated minimum heat output, and the efficiency of these solid fuel burners at this heat output is likely to be lower than typical test results, with higher pollution levels. Recently introduced clean air requirements for solid fuel burners may be compromised by being used at such low heat outputs.

16.5 Conclusions

A practical method of estimating net heating energy has been developed and demonstrated to work with an accuracy of about ±20% by calibration against monitored gas and electric heating under normal, occupied house operation. For solid fuel burners the monitoring uses a single thermocouple plus monitored temperature and energy data, with house physical parameters based on a site survey. This method has been implemented on a large scale and it has been found that the installation and calibration time for each solid fuel burner is 30-60 minutes. The method failed in only a small percentage of cases.

The calculation method of Modera (1986) has been shown to overestimate the heat output of modern solid fuel burners, due possibly to their different design. As a single temperature was used to predict the heat output, it seems possible that different equations could now be developed based on the physical characteristics of the burners. The wide variation in solid fuel burner designs, the effect of the double burning chamber and the patterns of use makes the development of a similar model outside the scope of this study.

Occupant self-reported wood use surveys do not give reliable estimates of heat output, particularly if sub-seasonal data are required. Field monitoring based on our new method gives more reliable estimates, energy time-of-use information and quantifies the heat output. Generally the heat outputs are well below the levels used for laboratory testing.

One result of this work has been changes to the official New Zealand Government energy statistics. Solid fuel heating now accounts for about 20% of domestic sector energy consumption, so important that a change in policies is now required to ensure its contribution is included in long-term energy policy and planning.

17. LPG HEATER USE

This section discusses the ownership and usage of portable unflued LPG cabinet heaters, more commonly called LPG heaters. This analysis does not include the use of LPG appliances attached to fixed gas piping in the house (usually fed from one or more externally mounted 45 kg home gas cylinders).

This section compiles and updates the material presented in the HEEP Year 8 (Isaacs et al, 2004), HEEP Year 7 (Isaacs et al, 2003), HEEP Year 6 (Isaacs et al, 2002) and HEEP Year 4 (Camilleri et al, 2000) reports.

17.1 Background

The number of portable LPG heaters used in New Zealand has increased dramatically over the last 20 years. Table 104 gives the proportions of households for heating fuels from the Household Economic Survey (Statistics NZ 2002d, 2004). The proportion of households with portable gas heaters has increased from 2% in 1984 (the least popular of the eight heating types surveyed at that time) to 34% (508,000) in 2004 (second only to portable electric heaters). The increase in use of portable gas heaters is closely matched to the reduction in use of the other two types of portable heaters surveyed: portable electric heaters (reducing from 89% of houses in 1984 to 72% of houses in 2004); and portable kerosene heaters (reducing from 11% of houses in 1984 to 1% of houses in 2004).

Heating Appliance	1984	1990	1995	2001	2004
Portable Electric	89%	85%	79%	71%	72%
Other Fixed Electric	34%	33%	30%	27%	30%
Portable Gas	2%	10%	20%	33%	34%
Fixed Gas	6%	9%	11%	12%	11%
Portable Kerosene	11%	5%	2%	1%	1%
Wet-Back Fire	NA	21%	19%	15%	14%
Open Fire	49%	32%	25%	17%	16%
Slow-Combustion Fire	27%	30%	34%	33%	32%
Central Heating	5%	5%	5%	5%	5%
Electric Night-Store	NA	NA	10%	9%	9%

Table 104: HES Household Heating Appliances

17.2 Heater numbers

The monitoring for HEEP in 2003 and 2004 saw a large increase in the number of LPG heaters encountered in the sample households. The selection process commenced with the major population centres followed by minor centres, leaving minor urban and rural areas to the last two years of monitoring.

Figure 90 provides a comparison of the observed number of LPG heaters per household for city (the urban level is either major urban or secondary urban) or small town/rural (the urban level is minor urban or rural). While there is a noticeable difference in the means (the number of LPG heaters for cities is 0.35 per household whereas it is 0.52 for town/rural centres), the wide range of variation in the numbers of LPG heaters per household suggests that additional factors need to be considered. The size of the data points in Figure 90 is proportional to the total number of households in that region or cluster.

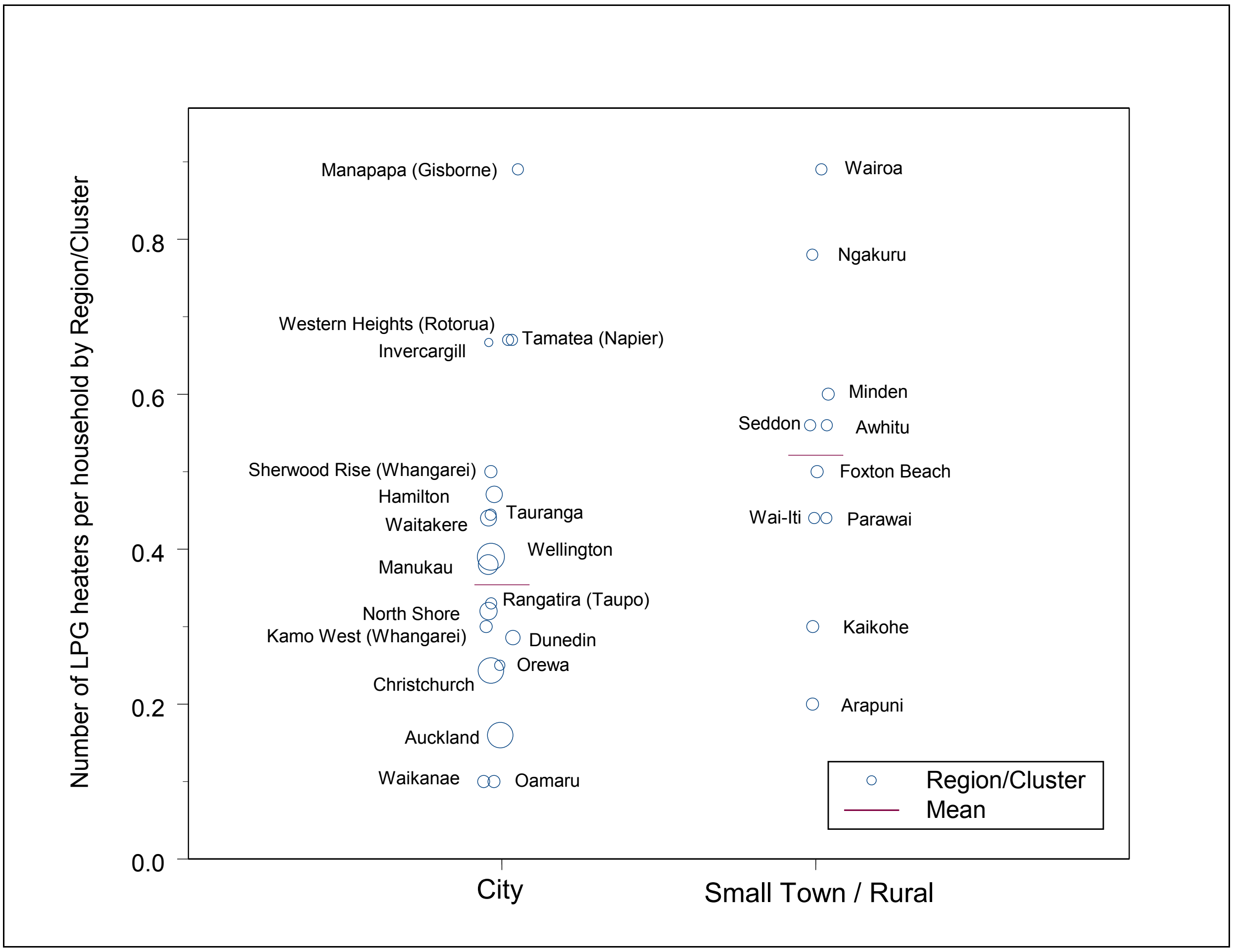

Figure 90: LPG heaters per household in city and small town/rural areas

As Table 105 shows, the preliminary total number of LPG heaters in the HEEP random sample was 157. A further 17 heaters were also encountered in the non-random HEEP dataset comprising replacement households, special sample houses (Hamilton pensioner houses) and pilot study houses (Wanganui).

	Households in random HEEP sample			LPG heaters in random HEEP sample	
HEEP monitoring period	**Number**	**With portable LPG heaters**	**With portable LPG heaters (%)**	**Number**	**Average number per household**
1999 †	41	16	39%	16	0.39
2000	17	7	41%	8	0.47
2001/02	97	27	28%	28	0.29
2002 †	47	10	21%	10	0.21
2003†	99	38	38%	38	0.39
2004	97	54	56%	57	0.59
TOTAL	398	151	38%	157	0.39

Table 105: Ownership of LPG heaters in the HEEP sample

† Figures have been revised from previous HEEP reports

The HEEP Year 7 report (Isaacs et al, 2003) reported on average 0.31 LPG heaters in use per household. Table 105 shows that a preliminary figure for the total number of LPG heaters per household in the complete random HEEP sample was 0.39. Taking the number of private dwellings in New Zealand in 2004 as approximately 1.5 million (Statistics NZ, 2004) the HEEP sample would infer that there were approximately 585,000 LPG heaters in New Zealand households in 2004.

The regular Household Economic Survey (HES) undertaken by Statistics NZ (1984–2004) provided information on the ownership of a number of appliance types, including gas heaters. It categorised gas heaters as either ‘fixed gas heaters’ or ‘portable gas heaters’. The portable gas heater category included portable unflued LPG cabinet heaters, as well as any portable unflued gas heaters that are attached to a piped gas supply via a bayonet plug.

The HEEP database has not distinguished between fixed and portable gas heaters, but instead has records of whether the gas heater was flued (and therefore fixed) or unflued (which could be either fixed, such as a hallway panel heater, or portable, via a bayonet plug). An examination of the available photos of unflued gas heaters in HEEP indicated that half were fixed and half portable. With a total of 35 unflued gas heaters in the HEEP sample, this would take the ownership of portable gas heaters per household to 0.43 (equivalent to 645,000 extrapolated to all New Zealand households for 2004), 90% of which are portable unflued LPG cabinet heaters.

The HES survey reported on the proportion of households with a particular type of heater and not the number of heaters per household. From the 35 additional unflued heaters in the HEEP sample, it is estimated that an additional 10 households had portable gas heaters, giving a total 40% of households (600,000 over all New Zealand) with portable gas heaters in 2004.

17.3 Heater types

The properties of an LPG heater were only recorded if the heater was stated as used and available for instrumentation at the time of the installation visit. The properties recorded were the make and model of the heater, whether the heater had discrete settings or a thermostat, whether the heater had radiant panels or was a convective heater, the number of settings and the gas consumption rates for each of these settings. Overall, 114 heaters had their details recorded (no details were recorded for the Wellington houses).

Ninety-six percent (109) of the heaters, with information recorded, were of a radiant panel design with the remaining five being of a convective ‘blanket’ design. Seventy-five percent (85) of the heaters examined had three settings (low, medium, high) with 11% (12) having an additional economy setting. One percent (2) of the heaters were of a compact two setting design, with these settings comparable to low and medium settings on the other systems. Nine of the systems (8%) were thermostatically controlled switching in panels as required. One system had one radiant panel placed horizontally at the bottom of the heater.

Figure 91 provides histograms of the gross energy output for each of the settings of each of the non-thermostatically controlled heaters, with Table 106 providing details on the number, mean and standard deviations of the levels of each of the heaters.

Setting	Number	Mean Gross Energy Output	Std. Dev. of Gross Energy Output
Economy	12	910 W	140 W
Low	105	1450 W	290 W
Medium	101	2540 W	360 W
High	98	3740 W	420 W

Table 106: Gross energy output for each heater setting of the non-thermostatically controlled heaters

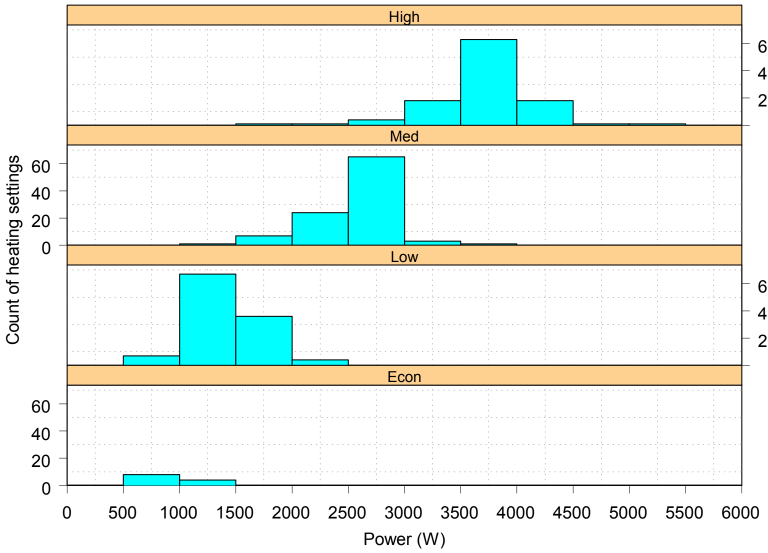

Figure 91: Gross energy output for each setting for radiant non-thermostat LPG heaters

17.4 Data availability

It is difficult to measure the energy consumption of portable LPG heaters. The flow of gas within a portable LPG is small and equipment to measure such low flows are rare. The method developed for HEEP was outlined in the HEEP Year 4 report (Camilleri, et al, 2000) and involves determining which combination of panels of the LPG heater are on at any one time. The status of each panel of the LPG heater is determined by measuring the temperature in front of each panel with a thermocouple junction. The outputs of all of these thermocouples are fed into a BRANZ logger placed next to the portable LPG heater and panel combinations are determined every five minutes. These combinations of panels are then associated with a particular power level for the heater and a time series of the energy use of the heater can then be created. An example of the response of the thermocouples for each of the settings for one particular heater is shown in Figure 92.

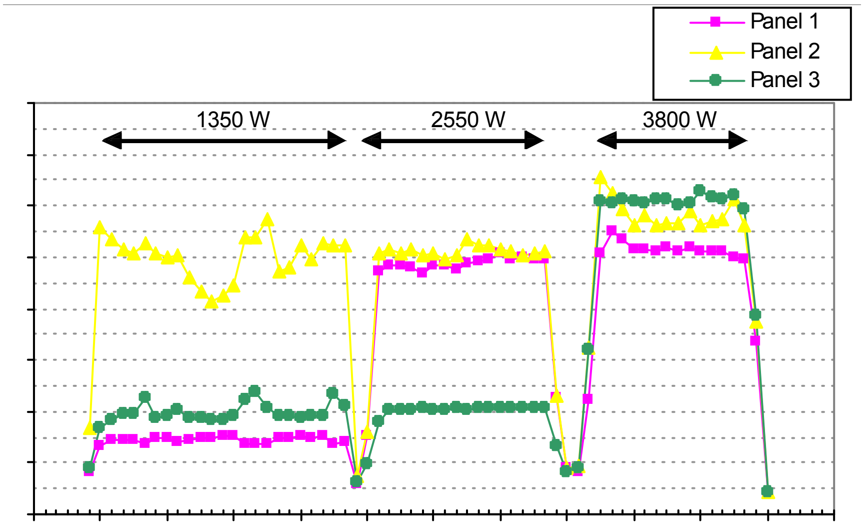

Figure 92: LPG setting determination for one heater

Assigning of settings for each record of the data logger is not without errors. For example, the 1350 W setting in Figure 92 can be identified as those records which have a thermocouple response for panel 2 greater than 800 and a thermocouple response for panel 1 and 3 below 500. If the threshold for panel 1 for this setting is set to 900 (which seems reasonable when examining the responses for the 2550 W and 3800 W settings) then the values around 11:00 would not be classified as the 1350 W setting. Table 107 provides an example of analysis of the classification of the settings of a number of individual download files for a particular portable LPG heater. The shading in Table 107 indicates those settings that can be identified to a particular setting of the heater. From the 'Assign setting' column it can be seen that settings are assigned to a recognised setting for over 99% of the time for this heater.

visit	all off	2nd on	1+2 on	All On	Intermediate (errors)					No. of five minute records	Assign setting	Assign error
	S000000	S101110	S111110	S111111	S111000	S001000	S100000	S101010	S101000			
4	100.0%									1840	100.0%	0.0%
6	96.7%	3.2%				0.0%	0.0%	0.0%	0.0%	8052	99.9%	1.9%
7	92.8%	6.9%	0.1%		0.0%	0.1%	0.0%	0.1%		9986	99.8%	2.9%
8	98.3%	1.7%			0.0%	0.0%	0.0%			9987	100.0%	2.3%
9	99.5%	0.4%			0.0%					6638	99.9%	3.3%
a	99.3%	0.7%			0.0%					7101	100.0%	1.9%
b	100.0%									6960	100.0%	0.0%

Table 107: Setting assignment errors for one heater

Installing thermocouples in front of each panel of an LPG heater can mean dismantling part of the heater, which can take some time. Further time is required to determine the energy consumption for each of the settings of the heater. Previously the specialised heater preparation work (installing the thermocouples and determining the heater settings) was undertaken as a separate task from the general HEEP installation and was undertaken at a centralised site for each of the regions being monitored. As HEEP began the monitoring of houses from widespread locations around the country, the practicalities of maintaining the heater preparation and general HEEP installation as separate procedures became more difficult. A modified approach, including use of data from previously calibrated heaters, was developed in order to maintain data quality.

The data collection methods were developed while the HEEP study was collecting data from Wellington (1999 monitoring year). Consequently there is no usage information for the 16 heaters in the Wellington sample.

Normally only heaters reported during the occupant survey as being used were instrumented. Overall, 86% of heaters owned were reported as being used.

The reliability of the occupant response was accidentally tested in two houses. In one household the survey respondent reported that the heater was not used, but the heater was monitored. Data from this 'not used' heater shows that it was used on average for nine hours per week over winter. In another house, a second heater was monitored despite the survey response indicating it was not used, although in this case the recorded data confirms that the heater was not used.

17.5 Sample LPG heater use patterns

Figure 93 and Figure 94 provide an exploratory representation of the half-hourly data for a selection of portable LPG heaters used in the houses measured. In these graphs the y-axis gives the day of the year, while the time of day is given on the x-axis. The colours represent the heater power output – the darker the colour the higher the output. Missing data is indicated by the presence of the vertical grid lines. It can be seen that often the missing data is outside the expected winter heating period (e.g. during the summer) and it is thus of limited concern for analysis of the heater use during the cooler months.

While the time between records for electrical energy data is important and is seen to make a difference to the daily energy patterns (Pollard 1999), plotting the 10-minute data in place of the 30-minute data (as shown in Figure 93 and Figure 94) does not produce much of a visual difference in these graphs. However, the 30-minute data is easier to deal with, as it takes less time to process and display, so it was used for this particular display of data.

As with most exploratory graphing techniques, there is much information that can be gained from close examination of Figure 93 and Figure 94. Figure 93 compares the LPG heater usage between House 2 (a low usage house) and House 4 (a high usage house). The heater from House 4 is operated on a low setting over a fairly regular period in the evenings during winter. The day-to-day usage of the heater is also fairly consistent with the heater being used most days over winter (June, July, August). For a relatively short period in July the heater was used during the day. The usage of the LPG heater in House 2 is less predictable. Seldom is the heater used for more than two days in a row. The most popular time of use is during the day, but it is also used in the evenings. The heater is also used at different heating settings with some heating sessions only operated on the low setting and others including both medium and low settings.

Figure 94 provides LPG heater usage information from two households with higher usage. Both of the heaters in these homes are predominantly used on higher settings (medium for house 1 and high for house 5). The heater in house 1 is used mainly in the morning and the evening; however the timing is less consistent than for House 4. There is also an extended period of zero usage in August. This was due to a change in the members of household. After this period, the day-to-day usage of the heater appears to be slightly more consistent. It is also interesting to note that there is some usage of the LPG heater during January. The LPG heater used in house 5 is predominantly used on the high setting, with morning being the most popular time of day. Less usage of this heater is seen in the evenings than is the case for the other highly used heaters examined. The LPG heater in house 5 appears to be used fairly regularly on a day-to-day basis except for a period of zero usage in June. The duration of each heating session appears to be shorter than that for the other heaters examined.

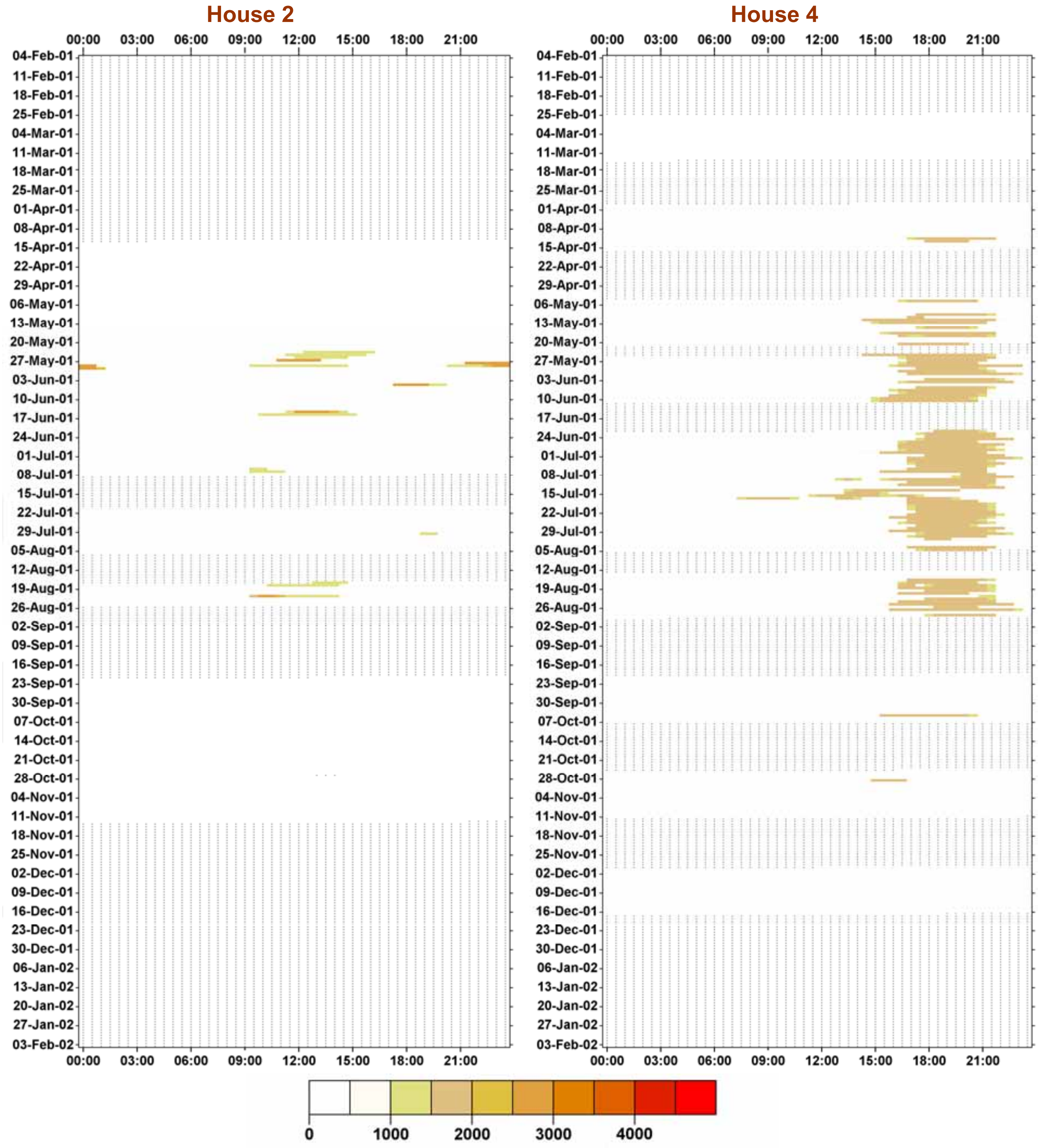

Figure 93:LPG heater use by time of day & day of year (Houses 2 & 4)

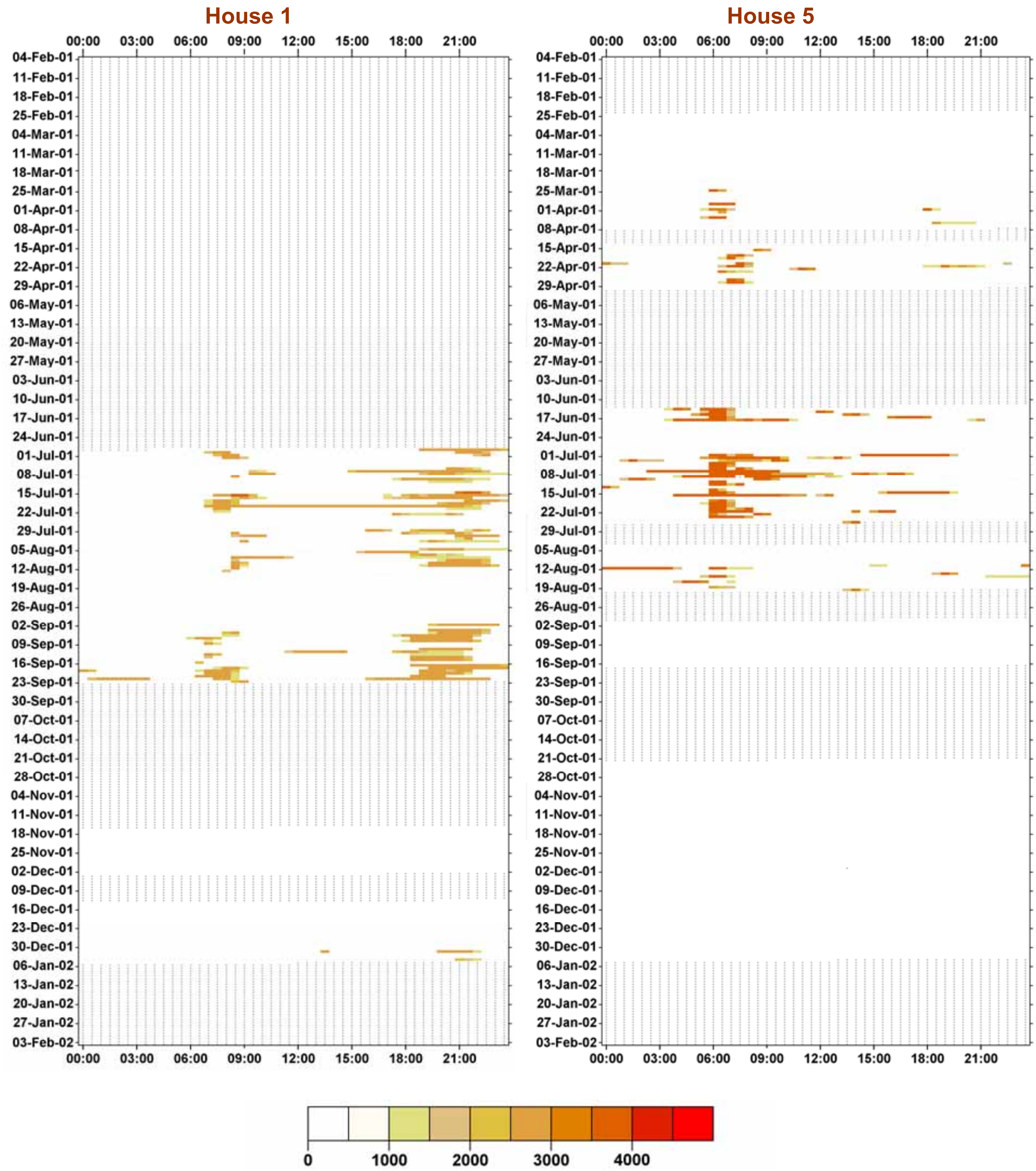

Figure 94: LPG heater use by time of day & day of year (Houses 1 & 5)

17.6 Patterns of use

Although an LPG heater may be present in a house, it may not be used at all during the year. For the LPG heaters for which data was collected, 31% (37 of the 121) were either surveyed as not used or had no usage recorded over the winter period.

Table 108 gives for each year of the study, the number of LPG heaters owned, reportedly used, the number available for monitoring the number able to be monitored and the number having winter use.

The column in Table 108 headed '*Available for monitoring (occupant issues)'* gives the number of heaters in each region that were present and could have been operated over the monitoring period. The reasons for this missing data were primarily occupant-driven and included such items as the heater being sold, the occupants moving out, heaters being borrowed temporarily or the heater developing a fault. In total 9 LPG heaters were not monitored due to occupant issues.

The column '*With data (monitoring issues)'* gives the number of heaters from the '*Available for monitoring (occupant issues)'* column that did not have complete data over the winter period due to problems with the data collection such as thermocouple wiring faults or logger faults. This column also includes LPG heaters that were not instrumented, particularly the 13 houses in Wellington when the monitoring technique had not yet been developed, and the occasional household where the installation team did not realise an LPG heater was in use. A total of 27 LPG heaters had monitoring issues that prevented them from being measured.

Finally, the last column of Table 108 headed '*With Winter use recorded'* gives the number of heaters that had non-zero energy use recorded over the winter. The remaining 16 of the 100 heaters with data had only zero energy use recorded (heater not used) over the June to August period.

Monitoring period	**Number of LPG heaters** ***Owned***	***Reported as used***	***Available for monitoring (occupant issues)***	***With data (monitoring issues)***	***With Winter use recorded***
1999	16	13 (81%)	13	0	0
2000	8	6 (75%)	5	5	4
2001/02	28	25 (89%)	20	19	13
2002	10	8 (80%)	6	4	4
2003	38	34 (89%)	34	28	26
2004	57	50 (88%)	49	44	37
Total	157	136 (87%)	127	100	84

Table 108: Usage of LPG heaters from the processed HEEP LPG sample

In order to examine length of use and energy consumption of the LPG heaters it was assumed that the heaters surveyed as 'not being used' had zero usage and zero energy consumption resulting in a total number of LPG heaters of 121. Histograms of hours of use (hours per week) and gas consumption (kWh per week) from these 121 heaters seen in Figure 95 and Figure 96 show high positively skewed distributions with over 50% of the heaters being used for less than 5 hours per week and over 40% of the heaters using less than 10 kWh per week. Table 109 provides the mean and standard deviations of the on-time and the energy consumption for all the 121 heaters, and also those that recorded non-zero winter consumption (84).

		Heater on-time (hours per week)		**Energy consumption (kWh per week)**	
	Number	**Mean**	**Std Dev**	**Mean**	**Std Dev**
All heaters	121	11	15	23	32
Heaters that were used	84	16	16	33	33

Table 109: Mean LPG heater duration and energy consumption

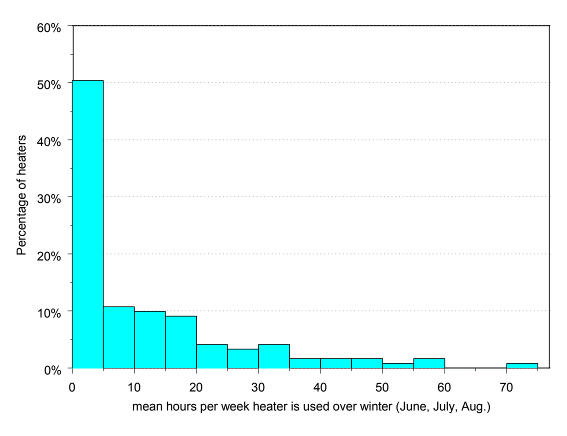

Figure 95: Histogram of hours of use LPG heaters (winter months)

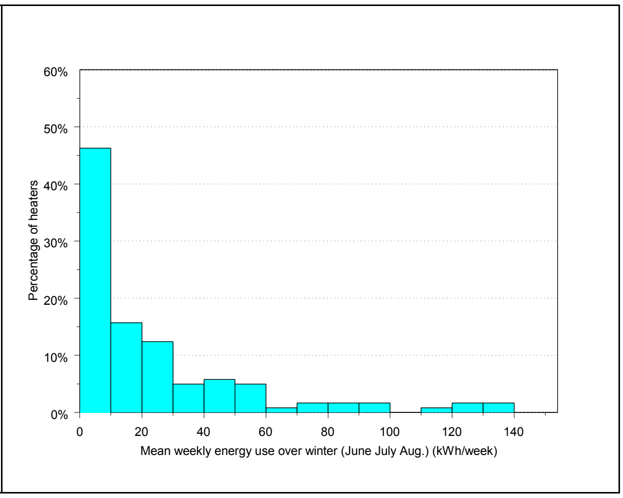

Figure 96: Histogram of the energy use for LPG heaters (winter months)

Figure 97 shows a histogram of the portion of the time each of the 84 LPG heaters that had their winter usage recorded, was operated in its primary setting. Over one-third of the heaters spent more than 90% of the time they were on in their primary setting.

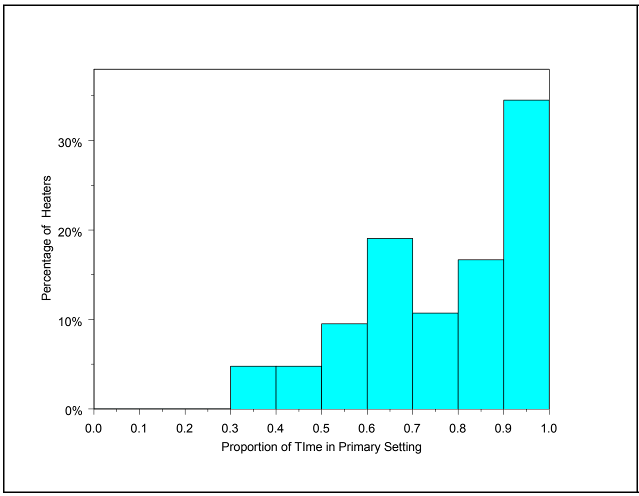

Figure 97: Proportion of the time spent in the primary settings for LPG heater

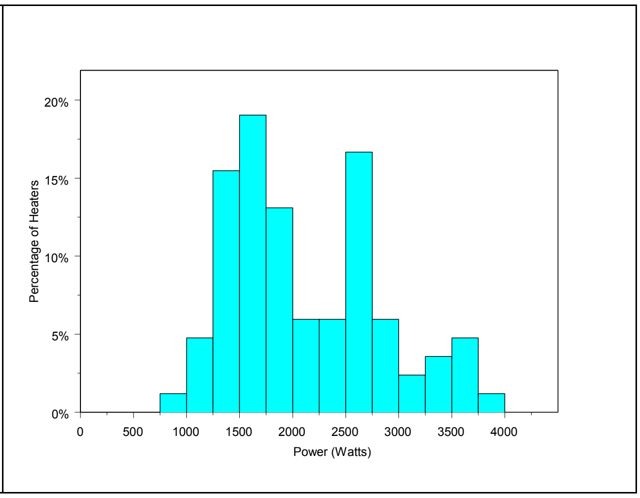

Figure 98: Expected gas consumption for the 'on' setting for each LPG heater

For these 84 heaters, 64% (54 heaters) had either a low (51) or economy (3) setting as the most preferred setting, 19% (16) operated their heater on medium most frequently, while 17% (14) had a preference for the high setting.

Figure 98 provides a histogram of expected gas consumption rate for operating LPG heaters showing increases in the number of heaters around the 1500 W, 2500 W and 3500 W levels correspond to common levels for the low, medium and high settings respectively. Overall the average expected gas consumption rate was 2100 W.

Figure 99, Figure 100 and Table 110 provide information on the amount of energy used and time spent in each of the settings for the 84 used LPG heaters. These again show the popularity of the low and medium settings, with the hours of use for each setting decreasing as the power of the setting is increased. In terms of energy consumption, both the low and medium settings have a similar average which is over twice that for the high setting.

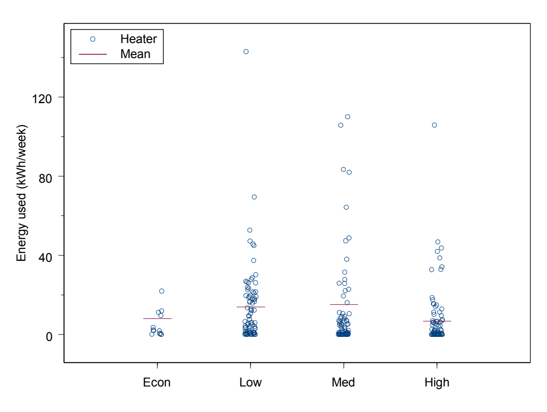

Figure 99: Energy used by each setting for heaters with winter usage

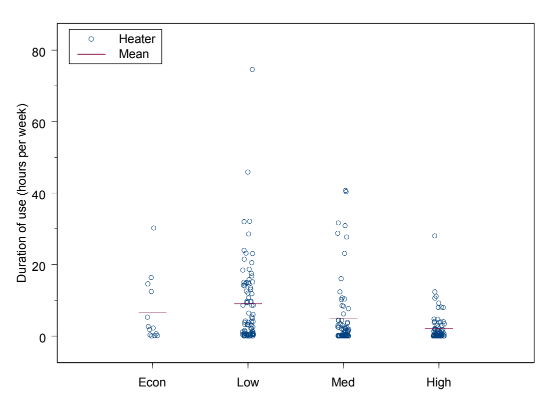

Figure 100: Time in each setting for heaters with winter usage

Setting	Heater on-time (hours per week)		Energy consumption (kWh per week)	
	Mean	Std Dev	Mean	Std Dev
Economy	7	9	5	7
Low	9	12	14	20
Medium	5	9	12	24
High	2	4	8	16

Table 110: Mean energy consumptions for each setting

As was the case with the total energy and total time in use, the variations in the time and energy use of each setting are large.

Figure 101 shows a plot of the cumulative energy use for all of the LPG heaters. It can be seen that many of the LPG heaters were not used at all. Half of the heaters used less that 6% of the total energy output of LPG heaters. The energy output was concentrated in a small number of heaters. Around 40% of the total LPG heating energy was used in only 20% of the heaters.

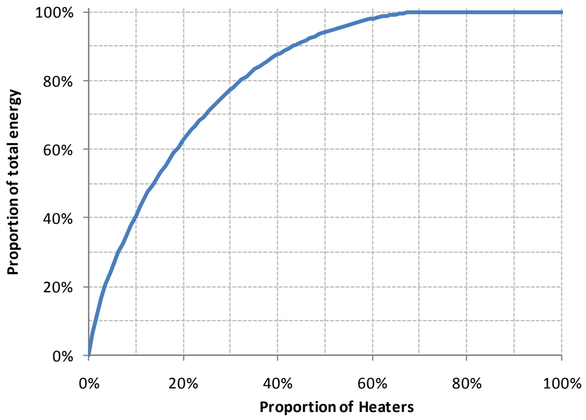

Figure 101: Cumulative plot of the energy used by each LPG heater

Figure 102 shows a map of New Zealand colour coded by the average amount of LPG heater usage within that area. LPG heater use generally increases as you move further south with the exception that LPG heater use in the Nelson-Marlborough area is very low.

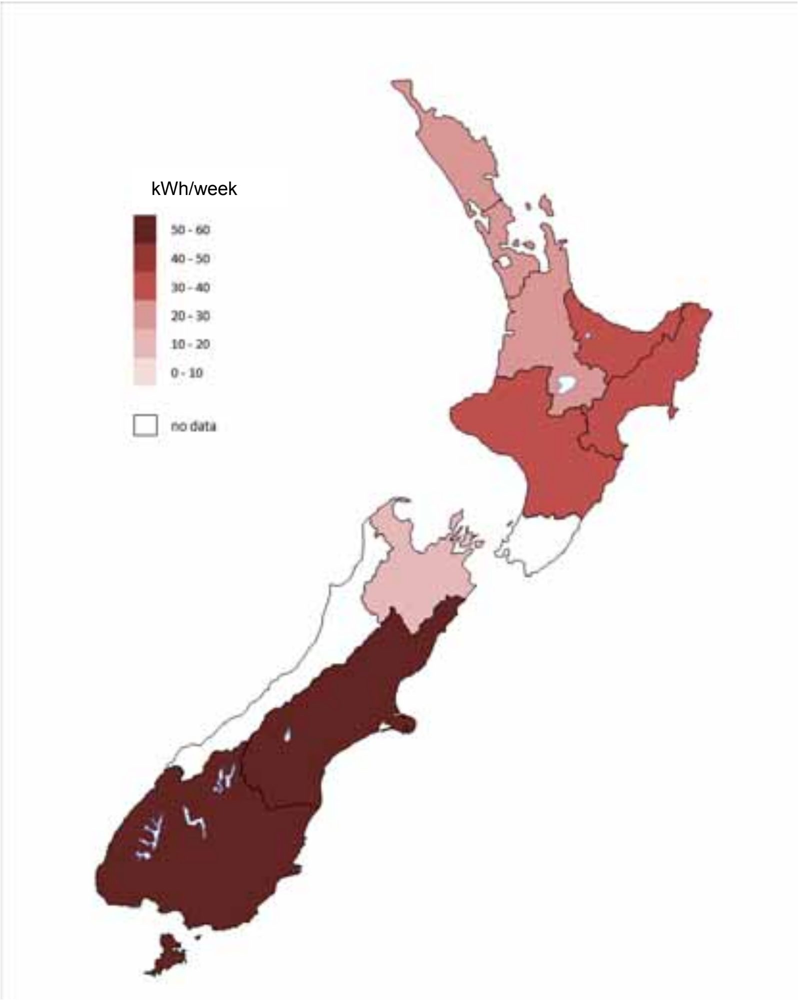

Figure 102: Wintertime LPG heater energy use (in kWh per week) for a number of areas around New Zealand

17.7 LPG heater and dehumidifier ownership

The operation of portable LPG heaters releases water vapour into the heated space. Dehumidifiers are becoming an increasingly popular method to reduce moisture levels so the ownership of both the source of moisture creating (LPG) heaters and moisture removing dehumidifiers is of interest. Table 111 provides a cross-tabulation of the total ownership of LPG heaters and dehumidifiers in the HEEP random sample.. Households without an LPG heater had a 22% chance of having a dehumidifier, whereas those with an LPG heater were approximately 40% more likely to have a dehumidifier with 31% of LPG heater owning households also owning a dehumidifier.

	No LPG	LPG	Total
No dehumidifier	192	105	297
Dehumidifier	55	46	101
	247	151	398

Table 111: Ownership of LPG heater and dehumidifier

18. EFFECT OF MANDATORY INSULATION ENERGY CONSUMPTION

Insulation has been required in new houses in New Zealand since 1978, intended to improve energy efficiency, reduce energy consumption and expenditure, and improve comfort and health. What has been the effect of insulating houses? On its own, insulation has been shown to be associated with less energy consumption. However, increases in heating temperatures, and the larger floor area of newer houses, have taken up some or all of the potential savings. There are major differences depending primarily on the heating type, with little or no overall reductions in electricity consumption, but significant reductions in other fuels. The implications for retrofitting insulation as an energy conservation measure are discussed.

18.1 Introduction and review

In an effort to improve comfort and reduce energy demand and the cost of space heating, since 1978 all new houses in New Zealand have been required to be insulated. So far there has been little research on the effects of this insulation requirement.

The 1971/72 study by the Department of Statistics (Department of Statistics 1976) compared two groups of houses; one insulated and the other uninsulated. It found that energy use was actually higher in the insulated group, although houses in this group were more likely to be in the colder climate of the South Island and were heated to a higher level. Since insulation was not required at the time it is possible that the houses that were insulated had this work carried out because the occupants wanted to heat the house extensively – in other words, a self-selected group.

A retrofit study by BRANZ on one staff house found that adding insulation increased indoor temperatures by about 1.4°C in winter, with a reduction in energy use of 300-400 kWh (Cunningham et al 2001). Another retrofit study by BRANZ on a selection of Wellington City Council owned pensioner flats showed increased indoor temperatures, improved comfort, and less heating energy use (Cunningham 2000).

The Health and Housing study conducted by the Otago School of Medicine was designed to measure the effects on respiratory health and health care (e.g. hospital admissions, GP visits) from the retrofit of insulation (Howden-Chapman et al 2007). Temperatures were also measured and some limited information on energy use was collected (electricity and gas billing records, self-reported LPG, wood and coal purchase). Analysis of this information showed that during the winter period temperatures in the bedroom increased after the retrofit of insulation by 0.5°C. Metered total electricity and gas consumption (from billing records) in the intervention houses was 8% less than in the control houses, and 19% less with self-reported LPG, wood and coal usage included. The energy data was not of high quality.

The Department of Physics, University of Otago undertook a study of 111 Housing New Zealand Corporation[20] houses in Southland,[21] where they retrofitted insulation and some other energy-efficiency measures (Lloyd and Callau 2006). Total electricity consumption was reduced by 5–9%, and 24 hour temperatures increased by 0.6°C in winter. The total energy reductions were higher, but the variation in non-electricity consumption was too high to make this result significant. Most of the houses already had some ceiling insulation which substantially reduced the improvement in whole-house heat losses achieved.

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[20] Housing New Zealand Corporation is the Government housing agency for social housing.

[21] Since New Zealand is in the Southern Hemisphere, Southland is the coldest region.

In overview, all of these studies have shown thermal insulation results in winter temperature increases of 0.5°C to 1.4°C, and small or no savings in energy consumption (although unfortunately electricity was often the only fuel monitored). However, most of these studies were carried out on particular groups of people (e.g. elderly pensioners in council flats, low income households with low health status, Housing New Zealand clients in Southland) so these studies are not representative of New Zealand as a whole.

There have been many studies of insulation retrofits in houses internationally. Most have been associated with large-scale insulation retrofit programs in an effort to understand the impact of the program. Most developed countries have introduced mandatory insulation requirements, with many precipitated by the oil shocks of the 1970s. However, there seems to be a lack of research on the effects of mandatory insulation.

One UK study tracked energy use and thermal comfort in domestic buildings (Shorrock and Utley 2003). The method used surveyed data on appliance types, efficiencies, and house thermal characteristics, and then modelled the temperature that would be required to give energy consumption equal to the known total energy consumption for the domestic sector. From 1970 to 2000 the average temperatures were modelled to increase by 6.2°C, and the penetration of central heating increased from 31% to 90%, but with the improved efficiency of heating systems and improvements to the house insulation energy consumption per house decreased by about 4%. This result is partly due to increasingly stringent Building Regulations for new houses, and partly due to the upgrade of existing houses. While the effect on new houses alone cannot be estimated from this report, it is clear that most of the potential savings have been taken up in increased temperatures and heating.

18.2 Household data

Analysis of the HEEP houses can be used to quantify the differences in energy use and space heating between pre- and post-1978 houses.

18.2.1 Heat losses and floor area

All the available HEEP houses were modelled in ALF3 (Stoecklein and Bassett 1999) to estimate their space heating requirements and heat loss. The required input data were taken from house plans and audit information collected when the monitoring equipment was installed. This was reported in Isaacs et al (2005) Section 8.

No clear cut distinction was found between the whole-house heat losses of pre- and post-1978 houses (Figure 103), although the average heat loss of the post-1978 houses (482 W/°C) is lower than the pre-1978 houses (586 W/°C). The differences are more pronounced in Figure 104 for the heat loss per m² where most post-1978 houses have a heat loss of <4 W/m²/°C, whereas most pre-1978 houses have a heat loss of >4 W/m²/°C.

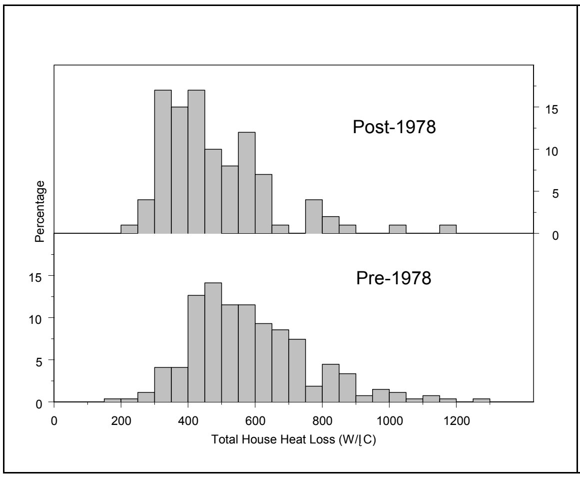

Figure 103: Total house heat loss for pre- and post-1978 houses

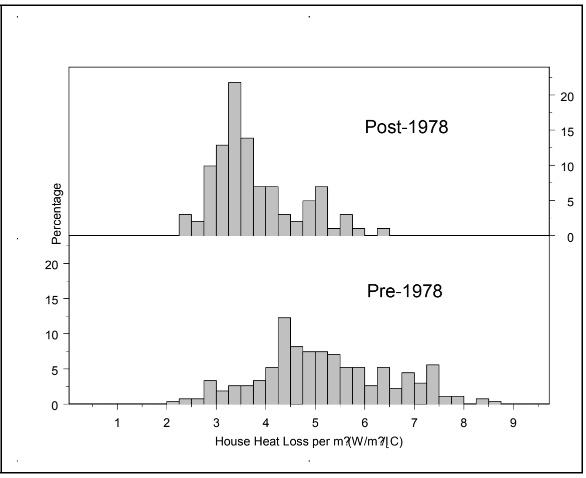

Figure 104: Heat loss per m² for pre- and post-1978 houses

The post-1978 houses have lower average heat losses but are larger in floor area than pre-1978 houses (Table 112). All things being equal (which they are clearly not) they would require about 20% less energy to heat to the same temperature and extent.

	Heat loss/m² (W/°C/m²)	SE	Total specific loss (W/°C)	SE	Floor area m²	SE
Pre-1978	5.2	0.1	586	11	119	2.5
Post-1978	3.8	0.1	482	16	132	4.6

Table 112: Heat losses for pre-and post-1978 HEEP houses

18.2.2 Temperatures and heating pattern

The post-1978 houses are on average 1°C warmer than the pre-1978 houses in the living rooms in winter evenings, and 1.2°C warmer over the whole winter 24 hours, with warmer temperatures for houses with larger heating systems (Table 113).

	Main fuel	Mean living evening temp °C	SE	Mean living 24 hour temp °C	SE
Pre-1978	Electricity	16.8	0.3	15.0	0.3
Post-1978		18.6	0.3	16.9	0.3
Pre-1978	LPG	16.8	0.3	14.8	0.2
Post-1978		17.7	0.3	16.1	0.3
Pre-1978	Natural gas	18.2	0.4	16.2	0.4
Post-1978		17.8	0.9	16.0	0.8
Pre-1978	Solid fuel	18.4	0.2	16.2	0.2
Post-1978		19.4	0.4	17.5	0.4

Table 113: Average winter temperatures by heating type

The HEEP Heat Index (introduced in Isaacs et al 2003) is a synthesised measure of house heating based on heating schedules and zones. It is calculated by assigning a score for each heating schedule and zone, and then summing. The most common schedule is winter evening living room heating only (which has a Heat Index of 7), and about half the houses also report heating the bedrooms in the evening as well (Heat Index = 14). The maximum Heat Index is 84 for 24 hour, whole-house heating.

There is no significant difference in the Heating Index between the pre- and post-1978 houses, suggesting that they are heated similarly in terms of schedules and zones (Table 114).

	Mean living room winter evening temp (°C)	SE	Mean living room 24 hr winter temp (°C)	SE	Heat Index	SE
Pre-1978	17.6	0.2	15.6	0.1	18.1	0.7
Post-1978	18.6	0.2	16.8	0.2	16.8	1.3

Table 114: Comparison of winter temperatures and Heat Index

18.2.3 Space heating energy consumption

Space heating estimates were prepared for all the HEEP houses by comparing the summer energy use with the winter energy use, with the difference assumed to be space heating. This was done for electricity and gas. Space heating for portable LPG heaters and solid fuel burners was monitored directly for all such appliances. This is a different method to the one used for estimating the space heating for the overall HEEP estimates, and gives a slightly higher average estimate of electric space heating (by about 25%). Further information on the methodology is in Section 14.

Table 115 below compares pre- and post-1978 house use of electric and 'all' (i.e. electric, gas, LPG, solid fuel) space heating. This is net energy – electricity is assumed to be 100% efficient, an enclosed solid fuel burner assumed to be 60% efficient, an open fire 15%, and a gas appliance 80% efficient.

	Electric heating (kWh/yr)	SE	All heating (net) (kWh/yr)	SE
Pre-1978	1,280	100	3,180	200
Post-1978	1,060	130	2,410	310

Table 115: Comparison of space heating energy

Comparing the pre-1978 and post-1978 houses, there is no statistically significant difference between their electric space heating energy usage. However this is seriously confounded by the location of the post-1978 houses, as there are more pre-1978 houses in colder climates. Therefore, merely on the basis of the colder climate they would be expected to use more space heating. There is a statistically significant difference in the 'All heating' energy in the post-1978 houses, however there are many possible causes. This will now be explored in more detail.

18.3 Statistical models of space heating

Statistical models were used to explore the effects of the various physical and socio-demographic input variables, such as pre-1978 status, floor area, income etc, on net energy consumption. These models can be used to attempt to separate the effects of various variables to allow the effect of the pre-1978 status to be compared on an 'all other things being equal' basis.

The process of developing these models involves an element of professional judgement to decide which of the possible model formulations to use. This decision was guided by the data, the goodness of fit, and common sense. Depending on which model was chosen as the final model, the effect of the various terms may differ e.g. one model might give an apparently larger effect of the pre-1978 status than another. Hence the estimates of the effect of various variables on energy consumption should not be interpreted as precise estimates. Standard errors are given for each of the variables, which gives some idea of how precisely that particular model defines them, but a slightly different and equally valid formulation of the model might give a slightly different value.

Unfortunately there are several features of the data that make the use of simple linear models problematic. The residuals (the difference between the actual value and the model prediction) are larger for higher heating energy consumption and they are not normally distributed, and the sample variance increases with the energy consumption. Both these features fail to meet two of the major criteria for the application of a linear model, which are normally distributed sample measurements with constant variance. The Generalised Linear Model (GLM)[22] is an extension of linear models that can accommodate such statistical distributions by using a non-normal distribution for the sample measurements (e.g. an exponential or gamma distribution). They can also fit the data in a non-linear sense by using link functions like logarithm, inverse or others. These features of the GLM allow the actual underlying structure of the data to be considered in the model and resolve the previous problems noted with the residuals.

The choice of GLM is a matter of finding which type best represents the data. The models used for this analysis use the gamma link function for the statistical distribution of errors, and a logarithmic function to link the predictor to the response. The logarithmic function causes the factors to be multiplicative, not additive as is usual with simple linear models. Overall, these were found to best deal with the non-normal distribution of the residuals and the skewed distribution of the energy consumption.

18.3.1 Electric heating – all houses

There is no significant difference in the national average electric heating energy consumption of the pre- and post-1978 houses (Table 5). However, this takes no account of regional variations or other factors.

For technical modelling reasons, 45 houses that used no electric space heating at all were removed from the analysis. The final model found the post-1978 houses were associated with (23±15)% less electric space heating, all other things being equal. The main fuel used for heating (whether electricity, LPG, gas or solid fuel) had a very large effect, associated with a drop of about (45±20)% in electric space heating in houses that mainly use non-electric heating (electric heating is used in most houses, although often only as back-up or secondary heating). The higher temperatures in the post-1978 houses were associated with an increased energy use of about (10±3)% and the larger floor area with a (6±1)% increase. The overall difference between the pre- and post-1978 houses was about (-10±15)%, which is not statistically significantly different from zero.[23]

We conclude that there is no significant difference between the amount of electric space heating in the pre- and post-1978 houses, and that the post-1978 houses are achieving higher temperatures over larger floor areas for approximately the same amount of electric heating as the pre-1978 houses, other things being equal. If the pre-1978 houses were insulated to the same levels as the post-1978 houses, and heated to the same (higher) temperature, the model predicts that the difference in electric space heating would be (-15±15)%, which again is not statistically significantly different from zero.

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[22] See *An Introduction to Generalised Linear Models* (2nd Edition) by AJ Dobson. Chapman and Hall/CRC, New York

[23] Since these GLMs use exponential functions, the means and standard errors are combined logarithmically. The ratio of standard error to the mean is not used to test for statistical significance; rather the confidence levels generated by the GLM SPLUS model are reported.

Part of the reason for the high statistical uncertainty is the large variation in electric space heating. Looking at houses that mainly heat with electricity should reduce this variation and give a larger difference.

18.3.2 Electric heating – houses mainly heated by electricity

The analysis was repeated for houses that use electricity as their main means of space heating. Reductions of energy use would be expected to be higher as more electricity is used, and it is used to heat warmer rooms such as living areas instead of being used more often in cooler bedrooms and for occasional heating (Isaacs et al 2006). This was found to be correct, with the average electric heating energy much lower in the post-1978 houses (Table 116). However, this comparison is seriously confounded by differences in climate, heating temperature and other factors.

The final model had factors for post-1978 status, floor area, region (representing climate), living room temperature and equivalised income.

The model of the mainly electrically heated houses shows a much larger effect of the post-1978 status on electric space heating – a decrease of (60±25)% in electric space heating.[24] Offsetting these factors were: the higher temperatures (+1.8°C in the post-1978 electrically heated houses and associated with increased energy use of (48±9)%); larger floor areas increasing energy use by about (5±4)%; and higher equivalised incomes[25] associated with an increase in energy use of about (10±4)%.

The net effect of the larger floor areas and higher temperatures of the post-1978 houses is associated with a difference in electric space heating of (-38±27)%, and this is statistically significantly different from zero at a 95% confidence level.[23]

If the mainly electrically heated pre-1978 houses were insulated to the same levels as the post-1978 houses, and heated to the same higher temperature, the model predicts that the difference in electric space heating would be (-41±27)%, which again is statistically significantly different from zero at a 95% confidence level.[23]

Differences in electric space heating energy for houses mainly heated by electricity are quite high. The low temperatures (15°C), and the comparatively small difference between inside and outside temperatures (about 5°C), means that insulation has a large impact on heating energy use, especially given that internal and solar gains contribute a large proportion of required heating energy.

	Electric heating (kWh/year)	SE	Mean living room temperature (24 hours) °C	SE
Pre-1978	2210	260	15.0	0.2
Post-1978	1470	330	16.8	0.3

Table 116: Mainly electrically heated houses space heating energy and temperatures

18.3.3 All heating fuels – all houses

It has been shown that there are significant differences between pre- and post-1978 houses on a national basis when all heating fuels are considered (electricity, gas, LPG, solid fuel), with the post-1978 houses using less heating energy. This is also true on a regional basis.

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[24] This is a large amount, also with a large statistical uncertainty (±42%). Other closely related models had smaller reductions.

[25] Higher equivalised incomes are, presumably, not caused by living in a post-1978 house.

A GLM was used to evaluate the effects of various factors. In isolation, the post-1978 status was associated with (45±11)% less space heating energy use. Higher temperatures in the post-1978 houses were associated with an increase in space heating energy use of about (32±3%), and floor area by about (6±1)%.

The net effect of the larger floor areas and higher temperatures of the post-1978 houses is associated with a difference in all fuels space heating of (-23±11)%, and this is statistically significantly different from zero at a 99% confidence level.[23]

If the pre-1978 houses were insulated to the same levels as the post-1978 houses, and heated to the same higher temperature (1.2°C higher), the model predicts that the difference in all fuels space heating would be (-28±11)%, which again is statistically significantly different from zero at a 99% confidence level.[23]

18.3.4 Total energy use excluding hot water

Models were also developed using the total energy use to cross-check the results of the analysis using space heating. The total net energy (all fuels) excluding hot water was used, for all fuels and for electricity only. The results appear in Table 117 and are in good general agreement with the results for space heating.

18.4 Summary of model results and discussion

Table 117 summarises the modelling results:

- ‘Post-1978 only’ refers to the % difference in the energy quantity associated with the post-1978 status, all other things being equal.
- ‘Post-1978, floor area & temp’ are the combined effect of the post-1978 construction, the larger floor area and higher temperatures found in the post-1978 houses, all other things being equal.
- ‘Pre-1978, post-1978 insulation & temp’ considers the impact if houses built pre-1978 had the same levels of insulation and rooms temperatures as found in post-1978, all other things being equal.

Note that the differences shown in a bold font in Table 117 are statistically significantly different from zero at the 95% confidence level.

In all cases, the ‘Post-1978 only’ was associated with a decrease in energy use. This demonstrates with a high degree of confidence that, all things being equal, the introduction of mandatory insulation in 1978 has led to improvements in energy efficiency of the housing stock. However, increases in temperatures and larger floor areas in the post-1978 houses have taken up part, and sometimes all, of any potential energy reductions.

The ‘Post-1978, floor area & temp’ results are mixed. They give a comparison between the pre-1978 and post-1978 houses, all other things being equal, and so correct for differences in climate, region, and sometimes income and life stage, between the pre-1978 and post-1978 groups. For example, since on average post-1978 houses are in warmer climates, this would reduce space heating energy consumption. With these corrections in place it can be seen that the post-1978 houses use less space heating energy for all fuels and less (i.e. total all fuels – hot water) for all fuels. However, they use the same amount of electricity. The group of mainly electrically heated houses are the only group that show less electric space heating in the post-1978 group compared to the corresponding pre-1978 group.

Fuel type	Quantity	House group	Post-1978 only (%)	Post-1978, floor area & temp (%)	Pre-1978, post-1978 insulation & temp (%)
Electricity	Heating	All houses	**-23±15**	-10±15	-15±15
Electricity	Heating	Elect. heated	**-60±25**	**-38±27**	**-41±27**
All fuels	Heating	All houses	**-45±11**	**-23±11**	**-28±11**
Electricity	Total – hot water	All houses	**-13±6**	-0.7±7	-7±7
All fuels	Total – hot water	All houses	**-26±4**	**-10±6**	**-14±6**

Table 117: Summary of model results

Note: differences in **bold** are significantly different from zero at the 95% confidence level.

'Pre-1978, post-1978 insulation & temp' is a prediction from the model of how the energy consumption of pre-1978 houses would change if insulated to the same level as post-1978 houses[26] and heated to the same warmer temperatures. This assumes no change in heating patterns and zones (we have already shown that the pre- and post-1978 houses are heated to about similar patterns and zones). Again, the overall result is mixed, with a similar outcome as the difference between the pre- and post-1978 houses. There are reductions in all fuels for all houses, but no reduction in electricity consumption, except for houses primarily heated by electricity.

In summary, it has been shown that mandatory insulation has led to warmer homes as well as reduced space heating and (total minus hot water) energy use. However, most of the energy reductions have come from non-electric fuels. The total energy savings for all fuels in the 27% of houses that are post-1978 would be about 2–3% of total energy consumption (all fuels), while the total electricity savings in the mainly electrically heated houses (about 8% of households) would be <1% of total electricity consumption.

18.5 Conclusions

The mandatory insulation of houses in New Zealand since 1978 has resulted in higher indoor temperatures and reduced energy consumption and space heating. Total net energy consumption excluding hot water was (10±6%) lower in the post-1978 houses, however total electricity consumption was not significantly different. Heating energy (all fuels) was (23±11)% lower in the post-1978 houses. Average temperatures in the post-1978 houses were higher, and average floor areas were also larger, and both of these factors increased energy consumption. These effects took up ~40% of the potential savings in all fuels, and most or all of the energy savings for electricity.

While the experiment did not retrofit insulation to pre-1978 houses the results give some idea of what might be expected. If the pre-1978 houses were insulated to the same levels as the post-1978 houses and heated to the same higher temperatures then the model predicts that total energy consumption of all fuels excluding hot water would be (14±6)% lower, and there would be no significant change for electricity (7±7% lower).

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[26] As noted, a pre-1978 house cannot be retrofitted to the same overall insulation level as a post-1978 house of the same design by only installing ceiling and floor insulation. Wall insulation, or double glazing, is also required but this is uncommon due to practicality and cost.

19. ESTIMATING HEAT LOSS AND THERMAL MASS

This section looks at estimating heat loss and thermal mass using the short term energy monitoring (STEM) method, which was developed for use in the BREHOMES (Shorrock et al, 1991) national heating model for the UK. STEM is used to determine whole house heat loss and effective thermal mass of existing houses by doing short term (several nights) of energy and temperature monitoring.

STEM normally requires that the house is heated and cooled down in a controlled way for several nights to obtain usable data. This approach was used early on in HEEP to determine the thermal parameters for four households. After this, the method was adapted for use in HEEP using the long term monitored data.

19.1 STEM thermal model

The STEM thermal model treats the house as a thermal circuit with one heat loss element and one heat storage element. The STEM methodology was applied under contract to a set of four HEEP houses by Robert Bishop in 1998 (Bishop et al, 1998) in order to test its applicability to the whole HEEP samplings strategy. This required that the house was vacated for one or more nights, and monitoring and heating equipment installed in the house to conduct the test. The house was heated to a moderately high, fairly uniform temperature to estimate the whole house heat loss coefficient, then heating was turned off and the house was allowed to cool down to estimate the thermal mass of the house.

The tested STEM model equation can be written as:

$$q_{heat} = UA \cdot (T_{in} - T_{Out}) + mC_p \left(\frac{\partial T_{in}}{\partial t} \right)$$

Equation 17: Heat model equation

where: q_{heat} = instantaneous delivered heat to house interior by internal gains and heating (W)

UA = whole house heat coefficient (W/°C)

T_{in} = interior air temperature (°C)

T_{out} = external air temperature (°C)

mC_p = thermal mass of the house (Wh/°C)

$\frac{\partial T_{in}}{\partial t}$ = rate of change of interior air temperature (°C/hr)

The model is based on night time measurements, so solar gains may be ignored, providing that the storage capacity of the building is not too large. Sources of internal gains include:

- electric, gas, and solid fuel use in the house
- solar gains
- gains from occupants.

19.2 Using STEM on HEEP houses in general

The STEM method could not be applied to the HEEP houses in general as it was not possible to gain the necessary access to the houses over one or more nights, and the costs of doing this measurement in the field is high. An alternative method was developed so that the actual monitored data from HEEP (energy and temperature) could be used to estimate the STEM parameters of whole house heat loss and thermal mass without the need to do an invasive field study.

For the HEEP houses only the monitored energy inputs were available, and solar gains and gains from occupants were not monitored. To use Equation 17 to estimate UA and mC_p for a house, the other gains must be accounted for in some way.

Solar gains are particularly difficult to deal with, as they vary with the weather, time of day, season, and occupant behaviour (such as the use of curtains). Avoiding daytime periods eliminates solar gains as a factor. Gains from occupants can either be ignored, or estimated by the number of occupants at home during the period of interest, which was surveyed for the HEEP houses.

The time lag in the heat transfer between the thermal mass and internal air, or between the interior and exterior, is not accounted for in this model. To minimise potential problems with these time lags, the model is fitted in two stages:

a) during periods of evening heating, when there are no solar gains, and the temperature in the house is maintained at a steady temperature – refer Equation 18

b) between about midnight and 6am, when no heating is supplied, and the house is cooling down – refer Equation 19.

As the rate of change of internal temperature is approximately zero during evening heating, the equation being fitted for period a) becomes:

$$q_{heat\ Evening} = UA \cdot (T_{in} - T_{Out}) + C_1$$

Equation 18: Evening heating period

where: C_1 = small error term

Data is selected from evenings when heating is applied, and the rate of change of temperature is low. Once the data is selected it is averaged by grouping according to the temperature difference. This step is required as the heating is often intermittent. The data is then plotted, for example as in the top graph of Figure 105. The fitted line is the model in Equation 17, with an extra term to account for thermal mass effects.

Even a small change in internal temperature represents a significant amount of heat absorbed or released by the thermal mass. At the point T_{in}-T_{out}<0 the internal temperature is lower than the external temperature, and if T_{in} is well below the desired temperature then a large amount of energy must be used to warm up the thermal mass. This is heating energy applied by the occupants without having any appreciable effect on raising the indoor temperature above the outside temperature. This often occurs when people come home in the evening to a cold house. The amount of this warm-up power is probably more closely related to the heating equipment used and the occupants' heating behaviour than to the thermal properties of the building. It is called the warm-up load, and is ignored by the robust line fitting technique. The slope of the line is UA.

For the unheated night time period, q_{heat} is assumed to be either much smaller than the other terms or constant, and the equation being fitted for period b) becomes:

$$q_{heat\ Night} = UA \cdot (T_{in} - T_{Out}) + mC_p \left(\frac{\partial T_{in}}{\partial t} \right) + C_2$$

Equation 19: Night time unheated period

where: C_2 = constant heat from internal gains

In this case, data is selected from the early morning period on days when no dedicated heating is applied, and the house cools down steadily. Data are averaged by grouping according to the rate of change of temperature. The data are then plotted as shown in the bottom plot of Figure 105 and a line fitted. The slope of the line is mCp/UA. By using the slopes of two independent line fits, the intercept terms are not important. The intercept term represents unknown constant internal gains. Provided these unaccounted gains are constant over the period of interest, they can be ignored.

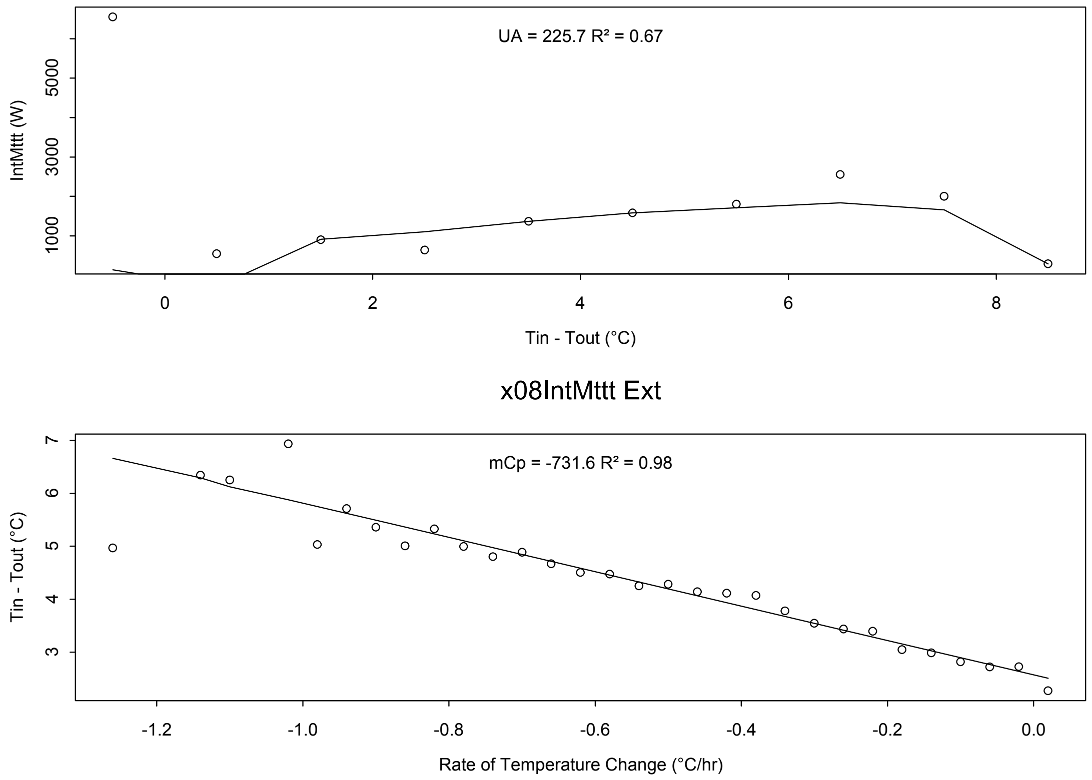

Figure 105: Fitted model plots

19.3 The STEM Model for a discrete time-series

The STEM model can be run to predict the internal temperature, or internal load in the house. To do this on the discrete time-series data, the STEM equation

$$q_{heat} = UA\,(T_{in} - T_{out}) + mC_p(\partial T_{in}/\partial t)$$

was converted to a difference equation as follows:

$$(\partial T_{in}/\partial t) = (UA\,(T_{in} - T_{out}))/\,mC_p - q_{heat}/\,mC_p$$

The time-series of data samples the continuous data at times $t_0, t_1, t_2 \dots t_n \dots$ To convert to a difference equation the differential term $(\partial T_{in}/\partial t)$ is approximated by:

$$T_{in,n+1} - T_{in,n} = [(UA \cdot (T_{in} - T_{out}))/\,mC_p - q_{heat}/\,mC_p\,]\,\Delta\,t$$

where $T_{in,n}$ is the internal temperature at time t_n, and similar notation for the other variables, and Δt is the time between timestep n and n+1. So the internal temperature in the next time step is approximated in Equation 20 as:

$$T_{in,n+1} = T_{in,n} + \left(\frac{UA \cdot (T_{in,n} - T_{out,n})}{mC_p} - \frac{q_{heat\,n}}{mC_p} \right) \cdot \Delta t$$

Equation 20: Internal temperature

This equation uses Eulers method to do the approximation[27].

19.4 Estimation of energy loads

The difference equation can be used to estimate the energy loads within the house, if the internal and external temperatures are measured. Rearranging the equation as:

$$q_{heat\,n} = -mC_p\left(\frac{T_{in,n+1} + T_{in.n}}{\Delta t}\right) + UA\cdot(T_{in,n} - T_{out,n})$$

Equation 21: The difference equation

shows how this is implemented. A simple calculation on the temperature time series gives an estimate of the energy load time series. By subtracting the measured internal load (i.e. the sum of electricity, gas, and other loads in the house) time-series, a measure of the so-called ‘missing load’ is found. This missing load could include:

- solar gains
- metabolic gains from people
- unmeasured loads
- hot water standing loss.

19.5 Calibration by prediction of internal temperatures

To successfully predict internal temperatures and applied heating, the internal load of the house must be known or estimated accurately. With whole house heat coefficients of around 300 W/°C, an error of only 100 W (about the metabolic rate of a single person) gives an error of 1/3°C in temperature. Solar gains may be much higher than this, even several kW, and so are a very important energy source. It was found that failing to account explicitly for solar gains leads to gross errors in temperature predictions. Using the equation for missing loads enables the identification and allocation of these loads, as well as providing a check on their magnitude.

Solar gains for a HEEP house are modelled by calculation of the solar insulation through windows. SUNCODE-PC routines were adapted and implemented in S-Plus to do this. Information required is:

- solar radiation, direct and total
- window width, height, orientation, shade size
- horizon angle.

To make predictions of applied heated based solely on meteorological data, a profile of internal loads excluding heating must be used, along with an assumed heating set point and schedule.

19.6 STEM prediction

The STEM model can be run as a predictive model to predict the heating requirements for a house based on meteorological data. So far the results have not been as good as desired. Particular problems are the applicability and accuracy of the assumed heating set point and heating schedules. The extrapolated heating energies are extremely sensitive to these parameters.

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[27]. D. L. Powers. *Elementary Differential Equation with Boundary Value Problems* Publisher Prindle, Weber and Schmidt, Boston. Chapter 6, pg 314.

19.7 STEM results

The STEM model was applied to selected HEEP houses to attempt to determine whole house U-values and thermal mass levels.

For each data subset described below, the 10-15 minute time resolution data was grouped according to temperature, and averaged. Internal temperatures were calculated as a simple average of all internal temperature sensors.

The whole house U-value was estimated using selected periods of data during the evening hours after sunset. The heating was for the entire internal gain, including applied heating, electrical and gas load, and occupant load. Data was 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 106).

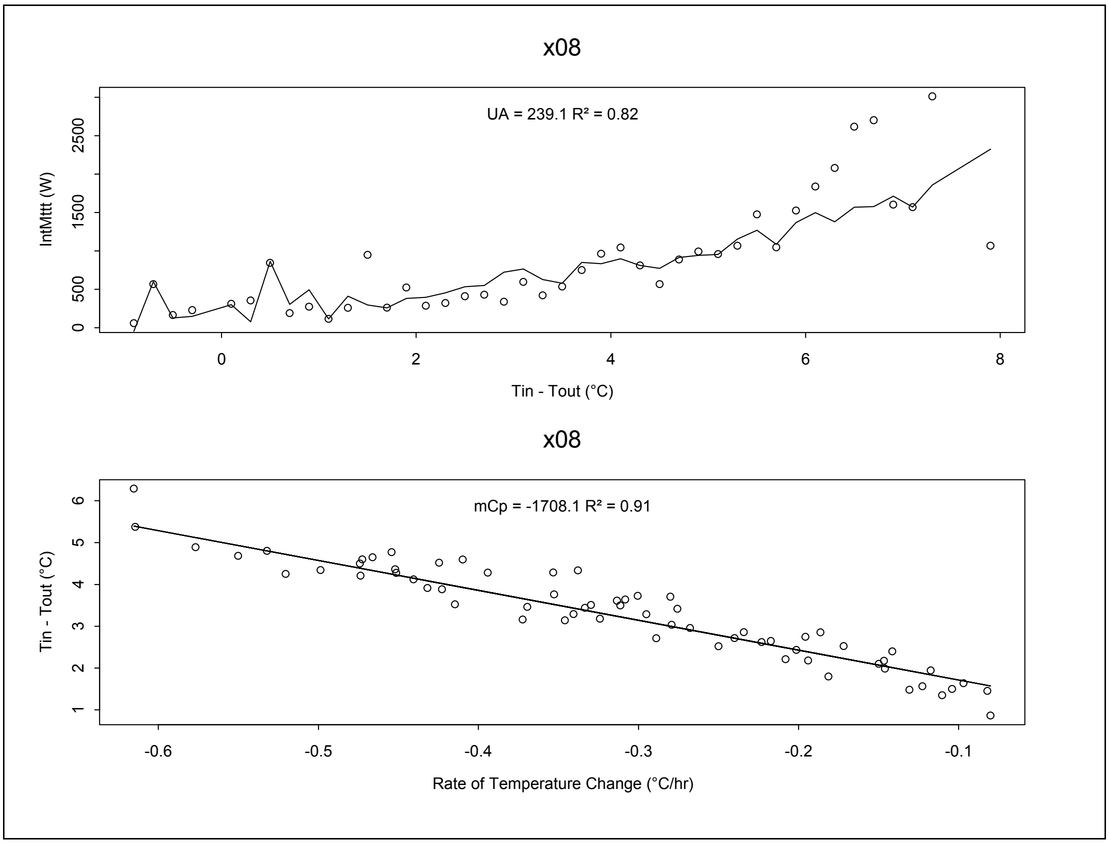

Figure 106: STEM model results

The whole house thermal mass was estimated using selected periods of data during the early morning, from around midnight to 6am (depending on the house). Data was 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 106).

The underlying data for the selected HEEP houses used for the initial trial are given below. There was good general agreement between the whole house heat losses from STEM and from ALF. The thermal mass figures were not in good agreement.

House	STEM U-Value (W/°C)	STEM Thermal Mass (Wh/°C)	Alf U-Value Inc Air Leakage (W/°C)	Alf Mass1 (Wh/°C)	Alf Mass2 (Wh/°C)
X02	625	9584	504	2155	313
X04[28]	376	3046	629	7175	398
X07	594	8144	482	4916	462
X08	239	1708	303	1732	146
X09	1305	10864	1119	5473	592
X10	205	2912	249	1676	201
X11	774	5856	633	2610	295

Table 118: Comparison of STEM and ALF U-value and thermal mass estimates

19.8 Practical use of STEM model for HEEP analyses

The STEM model for HEEP was developed and used over a period of several years. In general it was found to give good estimates of the whole house heat loss, however in some circumstances the method worked poorly or failed. These situations were:

- if the house was seldom heated in the evenings or heated to very low temperatures
- if a solid fuel burner or other unmonitored heating source was used.

The STEM method was used to estimate missing heat loads to allow the calibration of solid fuel burners. In this case the whole house heat loss and thermal mass were estimated used ALF3, and the STEM method used to estimate the heat output of the solid fuel burner. This proved to be very effective and was essential for the solid fuel burner calibration. More details of this application are given in the section on solid fuel monitoring.

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[28] House X04 is an apartment

20. HEEP APPLIANCE OWNERSHIP MODELS

The HEEP appliance ownership models are an attempt to understand some of the factors that influence the type and number of appliances that households have. For example, do households with more occupants have more TVs?

These models were developed for use in the HEERA model (see Section 6). However, practical issues prevents their full inclusion at this time.

The modelling is challenging, as there is often not a strong reason based on obvious physical or behaviour factors for variation in the ownership of a particular appliance. When people's behaviour or personal choice dominates variation then almost anything is possible.

There are often correlations between variables, e.g. income and floor area, and floor area and number of occupants. Sometimes these mask other relationships, or make a model appear to be nonsense. Relationships may also be non-linear (e.g. a large number of occupants (>5) is often associated with overcrowding), so the number of appliances might increase with the number of occupants up to a point, then level out or decrease.

20.1 Ownership data

The data is from the HEEP occupant survey and the power measurement audit, depending on the appliance type.

HEEP occupant appliance ownership information was collected as part of the HEEP survey questionnaire done during the installation of the monitoring equipment. The occupant was asked from a list of major appliances how many they had, and how often they were used. Appliances included heaters, cooking appliances, whiteware, and other common or major appliance types.

Another source of information is the HEEP power measurements. This involved an auditor going through the house and noting down all the electrical appliances in the house, recording various details such as type, make and model, label details and power measurements. This gave information on appliances that were not part of the occupant appliance survey, and also sometimes picked up appliances that the occupants had not reported. A total of 11,891 appliances were surveyed (see Camilleri, Isaacs and French 2006).

20.2 Methods

The modelling methods were various modelling techniques from S-Plus. The main techniques used were multi-variate linear models.

Various other modelling techniques were tried. Principal component analysis and factor analysis failed to give a compact set of transformed variables for the data sets trialled. Cluster analysis also failed to give cluster groupings that did not overlap extensively. These techniques seem to be of no practical value for modelling or exploring the HEEP appliance stock data. Decision tree models were trialled with some success, and have the advantage of being intuitive and visual, but could not be practically implemented in the HEERA model and so were not developed further.

Some data required by the HEEP models for individual houses will not be available on a regional basis. This is particularly problematic with tree models (initially trialled as appliance ownership models) as these models cannot work from aggregated data. To overcome this limitation, the data was aggregated on a location-by-location basis (groups of 6-24 houses depending on the strata or cluster size), and then linear models were applied to this data. This approach was very successful.

There are several other modelling methods that could be applied. Binary logistic regression could be used to model Yes/No categories of ownership. However, some houses have more than one of a particular appliance type. Ordinal logistic regression could be used in these cases. Another approach is to use Poisson regression models to model the number of appliances per house. Unfortunately these types of model are more difficult to use than linear regression, and the interpretation of the model terms is not always easy to understand. For these reasons, linear models on the average number of appliances by region were used.

Individual models were developed by exploring the effects of the various variables, keeping those that explained the most variation and discarding ones that did not make a useful contribution to the model. In cases where two separate terms were competing, with one tending to displace another, a decision was made on practical grounds – ie by choosing which variable was the most sensible to use for a particular appliance type.

20.3 Overview of models

The models are based on regional average data, such as average floor area. For categorical variables such as **LifeStage** it is the fraction of households in each region that belong to each category.

The models are not valid for individual households, as they will give nonsense answers e.g. negative numbers of appliances or very large numbers. They can only sensibly be used for the averages of large regions.

The model terms used are:

Degree Days: heating Degree Days base 15°C – the more the number of Degree Days, the colder the climate

Floor Area: total floor area excluding garages

Floor Area × No. of Occupants: interaction between floor area and number of occupants

Equivalised Income: total income divided by the square root of the number of occupants

Equivalised Income Q3 etc: fraction of households in the region that are in each quintile

LifeStage ‘pre-school’: fraction of household whose youngest member is pre-school age

LifeStage ‘school age’: fraction of household whose youngest member is school age

LifeStage ‘working age’: fraction of household whose youngest member is working age

LifeStage ‘retired’: fraction of household whose youngest member is of retirement age (>64)

Number of Adults: average number of adults per house

Number of Occupants: average number of occupants per house

Built before 1978: fraction of households that were built before 1978

Tenure: own with mortgage: fraction of households that are owned with a mortgage

Tenure: own without mortgage: fraction of households that are owned without a mortgage

Tenure: rent or lease dwelling: fraction of households that rent or lease.

An example is provided of how the calculation works for the number of TV decoders per house. The model terms are an intercept of 0.47, Equivalised Income Q5 term of 0.47, and LifeStage ‘school age’ term of -0.54. In a region with 20% of households in the school age, and 10% of houses in Quintile 5 for equivalised income, the model prediction would be:

0.47 + 0.47*0.1 - 0.54*0.2 = 0.41 TV decoders per household average for the region.

The model terms are given for all the models in Table 119. These models give some limited insight into why households have the appliances that they do.

The Model R^2 value describes how much of the variation in appliance ownership by region is explained by the model. Most are around 0.4, so about 40% of the variation is explained by the model. Some are a bit better, some not as good. The best by far at 0.81 is for heated towel rails.

Only clothes dryers appear to be influenced by climate, including in the model a term for Degree Days (which range from 195 in Kaikohe to 2,146 in Invercargill). None of the other appliance ownership models show any influence of climate.

Four models (computer, dishwasher, electric blanket and towel rail) show an influence of floor area. Other models that might be expected to include floor area, such as the various refrigeration models, do not. Floor area is weakly related to the number of occupants, and sometimes other terms (e.g. life stage) in some way also capture relationships around floor area and number of occupants. What is clear is that the socio-demographic characteristics appear in the models more often than house physical characteristics, such as floor area or house age.

The number of adults and number of occupants only appear in one model each. This is perhaps surprising. Ownership of many appliances might reasonably be expected to be influenced by the number of occupants, but this does not appear to be the case. Other socio-demographic characteristics appear to take precedence.

So what is going on here? Are factors such as life stage, income and tenure really more important or better predictors of appliance ownership than factors like floor area and number of occupants? It seems so. Acquisition of appliances is likely a very complex process, compounded by the various life stages that a household goes through as it forms, develops and breaks up, and the long operational life of many appliances. These life stages are often associated with particular activities – such as starting or ending careers, starting or raising a family, and retirement – and these activities can have a profound impact on the consumption patterns in a household. For example, a retired household might not have the means to acquire a large house or a lot of appliances, but may have acquired them in a previous life stage and still have them. Retired people may not have the means or need to replace them if they break, but may keep them until they break down or they move house.

The refrigeration models are particularly interesting. None of the four models show any influence of floor area or number of occupants, as might be expected. More people consume more food so it would be reasonable to expect some effect. This effect may be coming through the life stage and income factors. The school age term appears in all of them, and is a negative term for fridge freezers, so school age households are more likely to have a separate fridge and freezer than a combined fridge freezer. This makes sense in terms of the volume of food required for a school-age household with growing children. Also, a fridge acquired during previous life stages like pre-school or working age might have worn out or be too small.

Retired households most often have two refrigeration appliances, even if there is only one person in the household. Maybe what is happening is that many one-person retired households used to have two people, and one has died or gone into care, and it takes some considerable time for the remaining person to adjust their refrigeration appliances, if they ever do. Overall, retired households are likely to have a freezer.

The long working life and high cost of refrigeration appliances may result in households responding slowly to changes in their refrigeration needs, particularly since major changes in household requirements may correspond to major changes of life stage at which resources may be limited (e.g. new baby, retiring).

Income is particularly interesting. We have used equivalised income, which is the income divided by the square root of the number of occupants (see Table 62). Total income is usually not as useful, as it does not relate well at all to disposable or discretionary income. A household with a total income of $50,000 could have one occupant or six, and probably with a very different standard of living.

Equivalised income is strongly related to life stage, with the overall pattern being much higher equivalised incomes in households at the working age life stage, and very few households at the retired life stage above income Quintile 3. Quintile 5 households often have few people e.g. a single professional or a working couple. What is often seen in the appliance ownership models (and some energy models also) is an increase in the number of appliances up to Quintile 3, then a decrease, with Quintile 5 often as low as Quintile 1. The relationship between income and appliance ownership is often not a simple one.

Note: terms in **bold** explain the most variation and those in italics the least. **Model**	**Average Number per House**	**Model R^2**	**Intercept**	**Degree Days (per 1,000)**	**Floor Area (per 100 m^2)**	**Floor Area × No. of Occupants**	**Equivalised Income per $10,000**	**Equivalised Income Q3**	**Equivalised Income Q4**	**Equivalised Income Q5**	**LifeStage “pre- school”**	**LifeStage “school age”**	**LifeStage “working age”**	**LifeStage “retired”**	**Number of Adults**	**Number of Occupants**	**Built before 1978**	**Tenure: own with mortgage**	**Tenure: own without mortgage**	**Tenure: rent or lease dwelling**
Computer	0.85	0.43	-0.02		0.14	*0.0013*	**0.15**				-0.94									
Dehumidifier	0.22	0.30	-0.20				**0.08**													*0.26*
Dishwasher	0.41	0.35	0.04		**0.36**				*0.57*			-0.51								
Dryer	0.64	0.53	0.40	*0.10*			**0.11**	-0.36							-0.03					
Electric blanket	0.80	0.48	1.11		**3.32**		-0.49				-2.65		*-1.4*							
Freezer	0.68	0.46	0.09					**1.10**				1.13							*0.42*	
Fridge	0.66	0.33	0.09					**0.81**				*0.58*								
Fridge freezer	0.65	0.44	1.41					-0.72	*-0.81*			**-1.03**								
All refrigeration	1.99	0.52	1.59					**1.23**				1.27					-0.55		*0.65*	
Microwave	0.90	0.24	0.94					0.23									-0.14			
TV decoder	0.41	0.42	0.47							0.47		-0.54								
Stereo	2.56	0.44	2.74					**-2.16**		0.81				*0.88*						
Towel rail	0.55	0.82	-0.82		**1.45**		*0.11*										-0.62	-0.61		
TV	2.10	0.32	1.37								*-1.33*					0.36				**-1.11**
VCR	1.13	0.40	1.31					**-1.20**											*0.67*	

Table 119: Summary of the appliance ownership models

Note: terms in **bold** explain the most variation and those in italics the least. **Model**	**Floor Area**	**Floor Area x No. of Occupants**	**Equivalised Income**	**LifeStage “school age”**	**LifeStage “working age”**	**LifeStage “retired”**	**Microwave Used?**	**Number of Adults**	**Number of Occupants**	**Tenure: own with mortgage**	**Tenure: own without mortgage**	**Tenure: rent or lease dwelling**	**Volume of Refrigerator (l)**	**Year Refrigerator Made**	**Year x Volume**	**VCR Standby power**	**Total Hot Water Volume**
Dehumidifier																	
Instant gas hot water			**Pos**						*Pos*								
Electric hot water, delivered	*Pos*			Pos	Pos	Pos			**Pos**								Pos
Gas hot water, delivered									**Pos**		*Pos*	*Pos*					
Electric hot water, wetback connected, delivered				**Pos**	**Pos**	**Pos**			*Pos*								
Dishwasher				**Pos**	**Pos**	**Pos**			*Pos*								
Dryer	Pos		Pos						**Pos**		*Pos*	*Pos*					
Electric blanket																	
Electric jug	**Pos**		Pos						Pos		Pos	Pos					
Freezer													*Pos*	**Pos**			
Fridge													**Pos**	*Pos*			
Fridge freezer													Pos		Pos		
Lighting (fixed)	Pos	Pos															
Microwave									Pos								
Range		Pos					**Pos**		Pos		*Pos*	*Pos*					
Stereo			*Pos*	**Pos**	**Pos**	**Pos**											
Toaster																	
VCR																Pos	
Washing machine									Pos								

Table 120: Summary of the appliance energy models

20.4 Entertainment equipment

The type and use of entertainment equipment is changing rapidly as new technologies are becoming available. Historically, the New Zealand Television Broadcasters Council has surveyed the types of entertainment appliances in New Zealand households in some detail (Figure 107). This tracks the gradual introduction of new entertainment appliance types: first colour TVs, which gradually displaced black and white TVs, then grew so households with more than one TV set became more common. It was not until 1998 that the TV licensing fee became per household rather than per TV fee. The licence fee was dropped in 2000.

Home videotape recorders became available in the early 1980s, and achieved a rapid uptake to stock saturation levels in excess of 80% of households. Despite this technology now being obsolete, with only a few manufacturers worldwide still making VCRs, the stock levels in New Zealand households are still very high. The DVD player was introduced around 2000, and is rapidly heading towards saturation levels, growing at 10-20% per year. The price of DVD players dropped extremely rapidly, with cheap units sold for under $80.

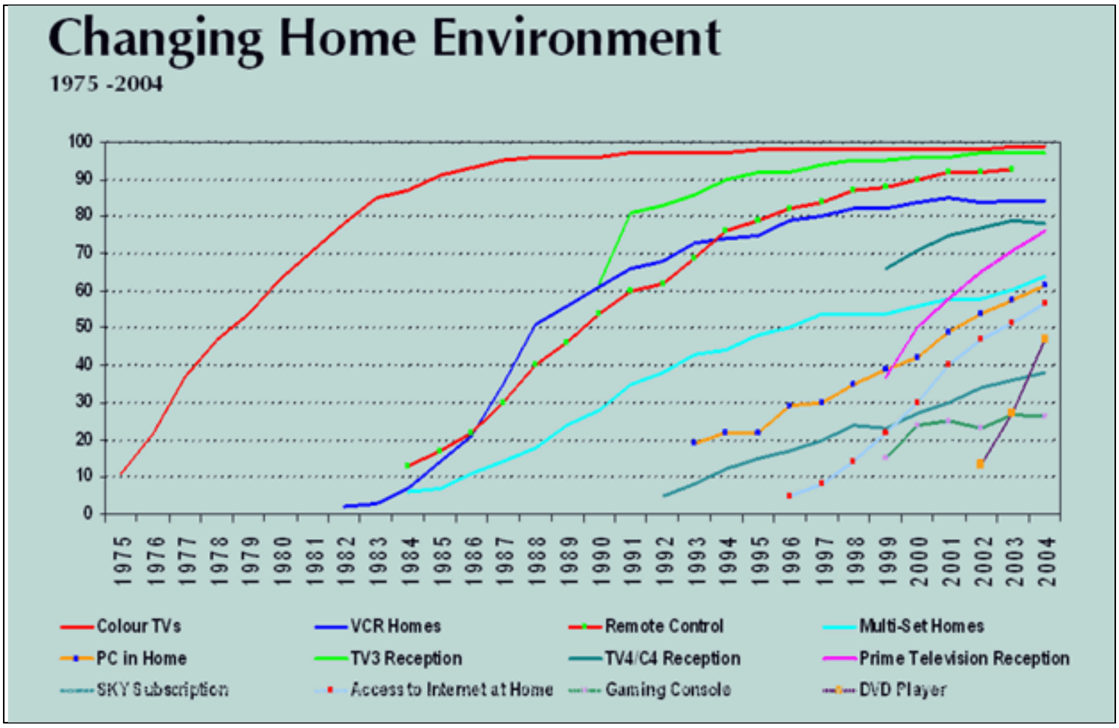

Figure 107: Long-term stock levels of home entertainment appliances[29]

How the home entertainment market will develop over the next 20-30 years is highly speculative, as new transmission technologies and new appliance technologies are rapidly being introduced.

New Zealand has now introduced a public digital TV network (Freeview satellite and terrestrial) alongside the existing privately owned Sky (digital and analogue) and Saturn (cable) networks. This will require a new set-top box for most households, although existing TVs should be compatible for some time. The planned switch-off date for analogue public TV broadcasts is 2012.

DVD recorders are becoming more common as prices are dropping. Other technologies are set to challenge the DVD recorder – most notable at the moment are various hard disk drive

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[29] Source: www.nztbc.co.nz/research/story.html?story_changing_home_enviroment.inc.

systems like the TiVo that is available in the US and other countries. Sky has introduced a decoder box with a built-in hard drive recorder. Some DVD recorders already have a large capacity hard drive installed for recording programs that are not intended to be stored and watched often. Various portable devices can also store digital video.

The home computer is also undergoing change ('convergence' is the technical term), with so-called media centre computers already available at a modest price premium. The media centre computer is a standard PC type computer with a front panel that looks like a stereo receiver unit with volume control and TV and radio-type controls, so that it can be used like a TV, radio or video recorder from a remote. It can record TV programs to the hard disk, like a TiVo unit. Microsoft has a version of the Windows operating system dedicated to this use, and the long-term vision seems to be a single PC/Windows-based computer that manages all video and audio media in the house, and feeds video and audio to monitors and speakers around the house by some kind of in-home network. How the average consumer will come to accept such a potentially complex set-up is debatable, given the number of people who cannot set up a home theatre system or program a VCR.

LCD and plasma TVs are rapidly gaining market share, and leading the move to large TV sizes. Whereas 25 years ago a 21" TV was large, 25-29" TVs appear to be average sized for new TVs, and larger sizes are available in CRT, LCD or plasma models. The CRT screen is rapidly becoming obsolete and is currently not sold anymore by major retailers as LCD and plasma models have taken over, with the likelihood of other novel display technologies in the future. The natural end point of these technologies is true flat screens printed on flexible plastic that can be hung like a poster. With their expected low cost and ease of installing it appears likely that many households could end up with many of these in rooms throughout the house, with a wireless media centre feeding video and audio. The current level of on average 2.1 TVs per house may be nowhere near saturation levels. CRT monitors currently use about twice the energy of a comparably sized LCD monitor (one-off measurement of 28 W for a 17" LCD monitor and 68 W for a 17" CRT monitor).

This is a future dramatically different from a slow saturation of current technology, with a gradual replacement by improved technologies that do the same thing as the previous technology. Trying to represent these possible futures in the HEERA model is a big challenge.

Current and anticipated trends are:

1) rapid increase in digital TV receivers once free-to-air transmission starts
2) increase in the number of TV screens per household
3) increase in the average size of TV screens
4) a gradual phase-out of CRT TVs as LCD, plasma and other types take over, possibly with reductions in energy use per TV
5) VCRs to eventually disappear, likely all but gone within 10 years, and replaced by DVD recorders, various types of hard drive systems, or media centre computers
6) large growth in home wireless networks for computers and audio-visual media.

Unless these new appliances have much lower power consumption and standby power than their existing equivalents, then energy consumption for entertainment appliances will increase beyond the current 3-5% of electricity consumption.

Proposed interim targets for the standby and power consumption of set-top boxes in Australia are 1 W for off-mode, 4 W passive, and 11 W on in 2006, and 0.3 W, 1 W, and 6 W respectively by 2012. Bringing these targets forward or introducing a MEPS would help ensure that the first wave of set-top boxes for free-to-air digital TV use the best available technology with the lowest power consumption, otherwise extra generation may be required.

21. STANDBY AND BASELOAD IN NEW ZEALAND HOUSES

For the first time, a nationwide statistically representative study of standby and baseload energy consumption has been completed in New Zealand. This is based on the data collected for HEEP.

The baseload of a house is the typical lowest power consumption when everything that is usually switched off is off, and was on average (112±4) W. This baseload represents the upper limit for the standby power consumption.

Standby power consumption was estimated at (57±4) W, heated towel rail use at (21±2) W, and faulty refrigeration appliances (compressors always on) at (15±10) W. Some appliances with standby, and some small continuous loads that are known to be excluded, make up another (11±4) W, leaving (8±12) W unaccounted. This represents a very nearly complete inventory of standby power consumption for New Zealand houses. It is unlikely that any major standby appliances are left unaccounted.

21.1 Introduction

Standby power is drawn by an appliance when it is not in operation but is connected to the mains. This can range from zero (e.g. a non-electronic clothes dryer) to 20 W or more (e.g. a television). These power levels may seem trivial on their own (1 W continuous power is approximately 9 kWh per year), but since most households have many such appliances, total standby energy consumption is usually a significant fraction of overall household energy use.

Standby mode is defined in the NZ standard (AS/NZ62301:2005, 2) as:

The lowest power consumption mode which cannot be switched off (influenced) by the user and may persist for an indefinite time when an appliance is connected to the main electricity supply and used in accordance with the manufacturer's instructions.

The **standby power** is defined as the average power measured in **standby mode**.

The baseload power of a house is defined in this paper as the typical lowest power consumption of the entire house when there is no active occupant demand and all cycling appliances (e.g. refrigeration) are in off-cycle. It includes the standby power of appliances (e.g. microwave ovens, VCRs, multiple TVs, video games, dishwashers etc), plus any appliances that operate continuously (e.g. heated towel rails, clocks, etc).

The baseload is important for two major reasons: first, it defines the lowest continuous power demand that must be met by a utility grid, and so has a large part to play in the utility load factor; and secondly, it includes a group of appliances that have the potential for demand reductions.

Early estimates of standby and baseload power consumption from HEEP have been instrumental in raising awareness of this important energy use in Australasia (Camilleri et al. 1999). Since then, standby power consumption reduction has been used as an energy conservation measure during power crises, and has been included in the joint Australian/New Zealand Minimum Energy Performance Standards (MEPS) for appliances.

Now that HEEP monitoring is complete, full, comprehensive and nationally representative estimates of standby and baseload power consumption can be prepared. This is a world first, as no other country has undertaken a study comparable to HEEP that could provide such estimates. Most other studies are non-random, with limited geographical or demographic coverage, or are based on spot measurements taken of new appliances often still in the retail store.

21.2 Review

Awareness of standby power began with articles in *Home Energy Magazine*. Meier (1993a) reported that utility bills during vacations were often almost as high as occupied periods due to the appliances that remain on, including electronic appliances. Sandberg (1993) published the results of a survey of some new appliances in Sweden, finding that most of them drew power when switched off – and described this as "leaking electricity". Meier (1993b) immediately reported these findings to a wider audience in *Home Energy Magazine* and noted that the phenomenon was an international one. The (now unsurprising) result that some appliances consumed more power in standby mode than in use was first revealed by Sandberg (1994). The secret of standby power was out.

Meier and Huber (1997) introduced their 1 W plan at the 1997 IEA conference as a long-term target for the maximum standby power of electronic appliances. Meier, Huber and Rosen (1998) subsequently took a detailed look at the underlying technical issues and found that most standby functions could be performed with 1 W or less of power, lending weight to their 1 W plan. The IEA convened a series of workshops and formally adopted the 1 W plan in 1999, proposing that the standby power of all new devices should be below 1 W by 2010 and calling on member countries to harmonise policy and regulation in this area (IEA 2005).

Studies of standby power have been conducted in a number of countries and have been compiled in a variety of review papers (Lebot, Meier and Anglade 2000; Meier 2001). Estimates per house at the time ranged from 20-60 W (Lebot, Meier and Anglade 2000) to 32-125 W (Bertoldi et al. 2002). It takes a lot of effort to track down all the appliances in a house, so many studies may have under-estimated standby.

Most reported papers were case studies of a small number of non-randomly selected houses and most also did not measure the standby of all appliances in the houses. To our knowledge the Jyukankyo Research Institute in Japan (Nakagami, Tanaka and Murakoshi 1997) and ADEME in France (Sidler 2000) have conducted the only studies of whole-house standby power consumption. Only the latter study measured a large number of houses, but as they do not appear to have been randomly selected this is not nationally statistically representative.

The pervasive nature of standby power means that every appliance in a house needs to be measured to assess the standby power consumption, and some studies have examined only a limited range of appliances. In general, studies are becoming more comprehensive in appliance coverage.

21.3 Standby & baseload data

Data on standby power comes from three sources within HEEP: **end-use data** – 10 minute monitored energy data from individual appliances; **power measurements** – spot measurements of the standby power carried out with a power meter at the time of the house installation; and **survey** – an occupant survey recording the appliance count and usage. By combining information from these three sources, a complete picture of household standby and baseload power consumption can be constructed. The monitored end-use data is the most detailed and provides information not only on the standby power level, but also on how long the appliance spends in standby mode. This information is hard to gather in any other way. There were 1,026 appliances monitored by this method.

Spot power measurements were carried out in all the HEEP houses by an auditor working through the house and recording every electrical appliance. A total of 11,891 appliances were surveyed. The information recorded included: type, make, model, serial number, label information, measured power consumption, measured standby power and the standby status (whether the appliance was in standby mode at the time of the audit).

How much information was recorded depended on the type of appliance, with appliances such as whiteware and entertainment equipment having all information recorded and minor appliances like blenders etc only having their presence recorded. Irrespective of the appliance type, if an appliance was found to be plugged in and switched on, a standby power reading was taken and the state recorded. This allowed some information about what percentage of minor appliances (such as chargers) are left in standby mode, and is a valuable complement to the end-use data. Standby power measurements were made on a total of 5,656 appliances.

Survey data was recorded for the major appliance types in all 398 houses, including their number and usage (e.g. constant, daily etc). Some additional information was collected for heating appliances, such as their type and which rooms they heated.

21.4 Methodology

The methodologies for estimating standby losses and baseload from monitored electricity data were first described in the HEEP Year 5 report (Stoecklein et al. 2001), and are outlined here.

21.4.1 Standby estimation

The analysis method for calculating the standby power and losses is based on the frequency distribution of the appliance power consumption. For example, a fridge compressor is on for most of the time, and when the compressor switches off the fridge has a standby power of about 17 W.

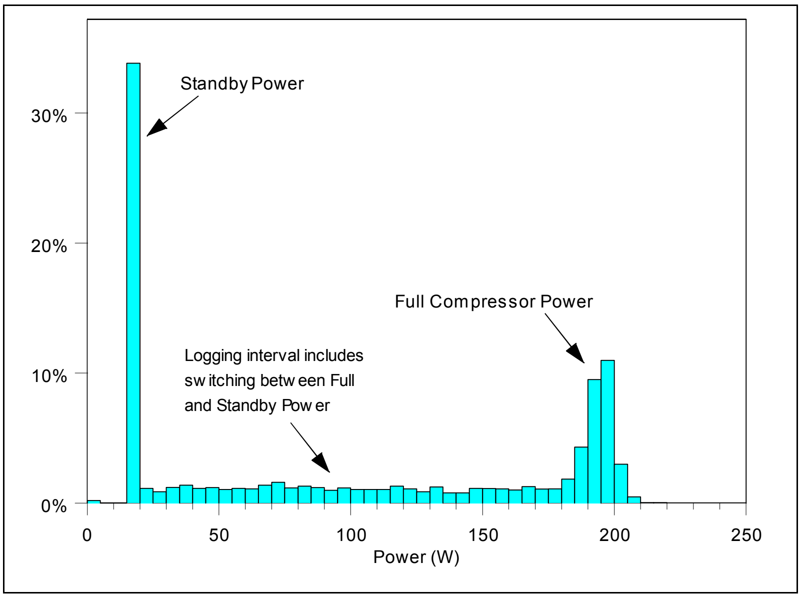

Figure 108. Fridge power use histogram

The frequency distribution for such a fridge is given in Figure 108. This histogram has two strong peaks: one at about 190 W corresponding to full compressor power; and another at about 17 W corresponding to the standby power. Power use in between these peaks involves the fridge switching on or off some time during the 10 minute sampling interval, so an intermediate power use is recorded.

The method for calculating the standby power is to find the standby power peak. Mathematically, the standby power is the **mode** of the distribution, which is defined as the value that occurs most often. For some appliances, the most common value is larger than the standby power as they rarely switch to standby. In these cases, the modal value of the data values that are lower than the mean power is taken. Once the standby power is known, the standby energy can be calculated. This is the energy consumed when the appliance is in standby mode, not when 'on' (in use) or disconnected from the mains. This distinction is important as some appliances, such as televisions, are not always left in standby mode.

21.4.2 Baseload estimation

The baseload of a house is the typical lowest power consumption when everything that is usually switched off is off. It is made up of the standby power of appliances, off-cycle power consumption of refrigeration appliances, continuous loads like heated towel rails, and other appliances that are always on (including faulty refrigeration appliances).

The estimation of baseload is analogous to the estimation of standby load, as the baseload can be thought of as the standby power load of the entire house. Estimation is more complex, because there are a large number of appliances switching on and off during the course of a day, so that the total power may only be rarely at baseload level and there is not usually a clear and distinct mode of low power. It may perhaps occur in the middle of the night, when everyone is asleep and all possible appliances are switched to off or standby. Note that overnight space heating is uncommon in New Zealand houses, and even if using electricity it would usually be thermostat controlled, so would be excluded from the baseload estimate.

To find the house baseload, the minimum monitored power for each individual day is evaluated and a histogram created. The baseload is expected to be the most commonly occurring daily minima, which should be at the low power end of the histogram. Calculating the mode generally gives a good estimate of the baseload, which was confirmed by visual inspection of 10 minute resolution plots of the total electricity for a number of houses. In households with many refrigeration appliances (or other fast switching automated appliances) the histogram of daily minima may not be so easy to interpret, as it is rare for all of the fast switching appliances to be off concurrently. In such cases, a good baseload estimate cannot be made as there is no distinct modal value.

For the HEEP sample households this rarely occurred, as the 10 minute monitoring interval was short enough to ensure that these fast switching appliances were usually resolved. Longer monitoring periods of 15 or 30 minutes increases the number of cases where the baseload cannot be properly estimated, and at 30 minutes most modern refrigeration appliances would never stay switched off for an entire monitoring interval.

The 10 minute monitoring interval was chosen as a sensible compromise of logger capacity, time resolution and time between downloads. Monthly downloads were done and the lowest capacity logger configuration at the start of the full-scale monitoring was about 40 days at 10 minute resolution. In the pilot study 15 minute resolution was used and the cycling of some refrigeration appliances could not be resolved. Several different types and versions of data logger have been used in HEEP and a lot of energy data was collected at 1 or 2 minute resolution, but aggregated to 10 minutes in pre-processing to match the monitoring interval of the temperature loggers. The storage capacity of the later BRANZ-made data loggers is much larger than the first versions. However, the 10 minute resolution and monthly download cycles were maintained throughout the project, although in some cases 4 channels of data could be monitored on a single logger where previously 2 or 4 loggers would have been required. To resolve fast cycling appliances, the monitoring interval must be less than the length of the off-cycle and the on-cycle so that there are always monitoring intervals where the appliance is fully off and fully on.

21.5 Results

21.5.1 Standby power and energy

The standby power and energy for all appliances measured are given in Appendix 1: Table Of Standby Power and Energy and grouped into categories. Several different values are reported:

- **standby power** – the power consumption in standby mode
- **standby energy** – the energy consumption in standby taking into account the amount of time spent in standby mode (annual average power over 8,760 hours)
- **standby energy per house** – standby energy multiplied by the average number of appliances per house (annual average power over 8,760 hours).

Appliance ranked by standby power	Standby power (W)	Appliance ranked by use of standby energy	Standby energy (W)
1. Fridge-freezer	15.0	1. VCR	9.0
2. Television set-top box	13.3	2. Television	6.3
3. Refrigerator (single temperature)	10.6	3. Stereo	6.2
4. Video cassette recorder (VCR)	9.4	4. Combination fridge-freezer	4.7
5. Instantaneous gas water heater	9.0	5. Computer (CPU & monitor)	4.4

Table 121. Top five appliances by standby power and energy

The five highest standby power appliances and the five highest standby energy appliances are listed in Table 121. These account for nearly half of the total household standby energy consumption. Note that three of the top five are 'home entertainment'. These appliances have high standby power consumption, as they are common and in standby for long time periods.

Table 122 shows the average energy use per house for standby is (57±4) W continuous i.e. the average New Zealand house is spending around $NZ90 ($US60) per year (at 18.7 c/kWh) just keeping these appliances powered-up waiting to be used.

Despite the prevalence of small chargers for cellular phones and other portable devices their actual standby energy consumption is small with less than 0.5 W average continuous power per house. About half the cell-phone chargers found were plugged in and on standby, as were about one-third of all other chargers. Generally cell-phone chargers only seem to be plugged in when required, and the more sophisticated types have a very low standby when they are not actively charging (~0.1 W). Older New Zealand houses (pre-1970s) often have a limited number of power outlets per room, and it is common to have only one outlet per room. This might contribute to these devices not being plugged in continuously.

Appliance	Standby power (W)	Standby energy (W)	Standby energy per house (W)
Entertainment	56.3	39.5	27.9
Garage	8.1	2.2	0.5
Kitchen	11.3	8.5	5.1
Laundry	4.1	2.5	2.2
Miscellaneous	35.8	28.1	5.9
Refrigeration	27.4	10.6	6.9
Home office	25.2	16.9	7.5
Space conditioning	9.3	8.5	1.1
Grand total	173	113	57±4

Table 122. Standby energy per house by appliance group

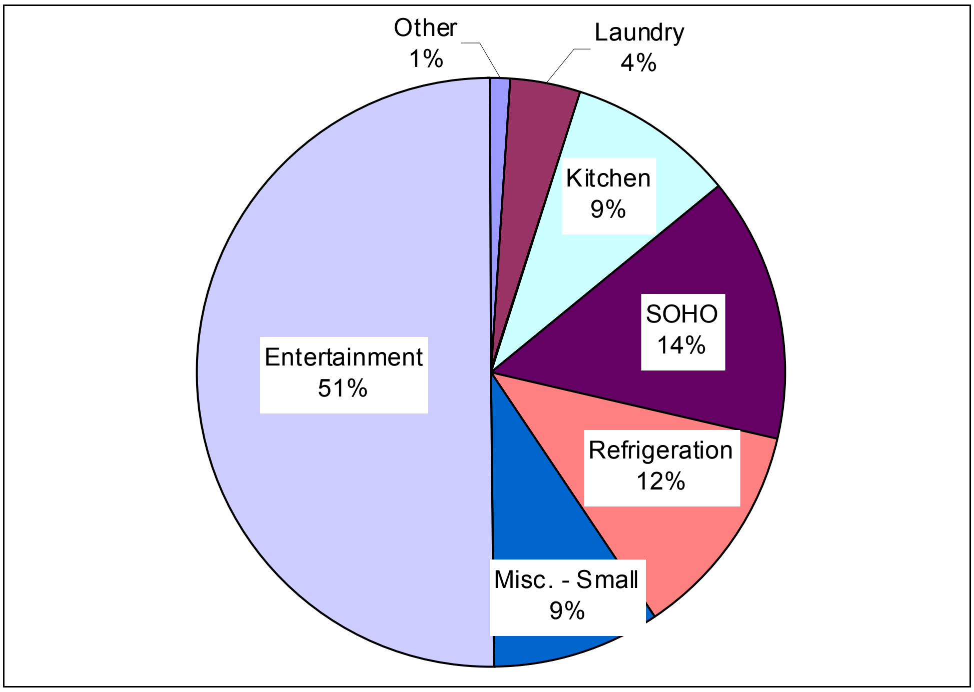

Figure 109: Breakdown of standby energy per house by appliance group

It is important to note that as the market penetration of appliances increases or decreases, the importance of their standby energy use changes. For example, VCRs are being replaced by DVD players/recorders. If each VCR is replaced by a more efficient, lower standby power DVD player then the national standby power demand of this appliance group will fall. However, if DVD players/recorders achieve a greater market penetration than VCRs, or they have similar standby power, then the overall impact may be unchanged or possibly even result in an increase in standby power demand.

If appliances were shifted to only 1 W standby, with 4 W standby for set-top boxes and 5 W for refrigeration appliances, this would reduce the standby load to roughly 21 W per house – a reduction of more than 60% (Cogan et al. 2006). Most of this reduction would come from entertainment appliances.

21.5.2 Baseload

The average baseload demand is (112±4) W. The baseload usually has a poor power factor, as it consists of various motors and inductive loads of small transformers. In a few HEEP houses the monitoring equipment also recorded reactive power, and the power factor of the baseload was typically 0.5-0.7. Reductions in baseload and standby therefore have a larger impact on utility load than the simple power consumption.

21.5.3 Heated towel rails

42% of New Zealand households have one or more heated towel rails, with an average of 1.3 per house in those that do have them. They are more common in newer houses and most newly built houses have one or more installed during construction.

The HEEP survey questionnaire recorded the number of heated towel rails and usage category (e.g. constant, daily etc.), and for the first 128 houses also the occupant self-reported hours of use. These hours of use were used to find the average hours of use for each usage category.

The average power rating of heated towel rails is also needed. This is not usually known by the occupants, and often no label is visible, and with fixed wiring it is not possible to undertake a power measurement. From the limited measurements of labels that were recorded, the average was (70±10) W.

The hours of use per week for each category can then be used to estimate the total energy consumption. Combining the number of heated towel rails with the usage and average power rating gives the average power use per house for heated towel rails of (21±2) W. Table 123 shows the 95% confidence interval (CI) is 17 to 25 W. For the 1.4 million households this is (30±3) MW, which is almost all continuous load.

	Average (W)	95% CI (W)
Per house	21±2	17-25
Per house with heated towel rails	50±4	42-59
Per house that uses heated towel rails	62±5	53-72

Table 123: Heated towel rail average power use

About half of heated towel rails are used constantly, and as the average is only 0.6 per house (across all houses), most of the energy is used in a small fraction of houses.

A single heated towel rail used constantly consumes about 700 kWh per annum, which can easily add 10% to the electricity bill. Reductions of energy use are readily achievable, for example by installing a timer switch.

In the UK, about 15% of houses have a heated towel rail (AMA Research 2003) and their electricity consumption could be as high as those in New Zealand.

21.5.4 Other standby and baseload

Some other small standby loads that were not monitored could be from the stove (notably the clock), fixed wired sensor lights, security systems and the electrical safety Residual Current Devices (RCD) now required on all new lighting and plug circuits in New Zealand. The RCD load might account for 3-5 W. RCDs are known as Ground Fault Circuit Interrupters (GFCI) in the USA.

Some lights may be left on overnight, and these have been estimated from the lighting circuit monitoring at (7±3) W (Cogan et al. 2006).

HEEP analysis published in the HEEP Year 10 report found that faulty refrigeration appliances consumed on average (15±10) W of continuous load per house. 16% of refrigeration appliances were found to be faulty with the compressor staying on for long periods of time (days to weeks) or continuously.

21.6 Conclusions

Table 124 provides an overview of New Zealand household standby and baseload, which totals (112±4) W continuous, equivalent to an annual cost of approximately $NZ150 (~$US100) per year. The 95% confidence interval is from 104 W to 121 W. Assuming 1.4 million houses, this is equivalent to about 160 MW of continuous load, or about 10% of the total average residential power demand.

Use	Load (W)
Standby	57±4
Heated towel rails	21±2
Faulty refrigeration	15±10
Minor loads	4±1
Lights left on	7±3
Remainder	8±12
Total	**112±4**

Table 124: New Zealand standby and baseload

Standby power consumption is estimated at (57±4) W, heated towel rail use at (21±2) W, and faulty refrigeration appliances at (15±10) W. Minor loads are (4±1) W and lights that are always on are a further (7±3) W, leaving unaccounted only (8±12) W which is not statistically different from zero. We can conclude that this therefore represents a complete inventory of standby power consumption for New Zealand houses.

22. FAULTY REFRIGERATION APPLIANCES

During the installation survey for HEEP, a number of refrigeration appliances were found that did not appear to switch to their off-cycle mode. Later visual inspection and analysis of the HEEP data confirmed this observation. The following analysis investigates the proportion of refrigeration appliances that are faulty, how much energy they waste, and what (if any) distinguishing characteristics they have.

All consumer appliances eventually fail and need replacement. For many appliances poor performance or failure is obvious, and there is no reason to believe that they are not discarded or repaired as needed. For example, if a video recorder stops playing, or has a poor image, it is noticed. Likewise, a clothes dryer motor or controller that fails will stop the appliance working.

However, for refrigeration appliances the signs of failure – poor temperature control and the compressor running continuously for long periods[30], especially in warm weather – are difficult to spot. Most refrigeration appliances do not have user readable thermometers, and many people may not notice a continuously running compressor. The appliance may continue to operate for years, even if it is no longer able to properly refrigerate food to safe temperatures or is very energy inefficient.

Refrigeration is a significant use of energy in New Zealand houses, measured by HEEP at (1,119±72) kWh per household per year; approximately 15% of household electricity and 10% of total household energy use (Isaacs, Camilleri, French et al, 2006; table 9). The average annual electricity consumption per appliance for refrigerators was (367±62) kWh, for fridge freezers was (621±30) kWh and for freezers was (663±39) kWh (Isaacs, Camilleri, French et al, 2006; table 10).

22.1 Review

There have been many programs internationally that target refrigerators for repair or replacement, and this is routinely done as part of household energy audits [Meier (1993); Parker and Stedman (1993); Witte (1993); Nelson (1993);Bos (1993)]. The challenges for the assessor are: 1) to remove poor performing appliances; 2) to not remove properly performing appliances; 3) to not leave behind too many poor performing appliances by being too conservative; 4) to complete the evaluation without spending too much time and money.

Few of these schemes have used energy monitoring to estimate the achieved energy savings, instead often relying on engineering calculations. Kelleher Environmental (2006) provides an overview of many refrigerator recovery programs in the US and Canada, looking at the type of scheme, the incentive used, and the estimated costs and energy savings. This was used to estimate potential savings of 1,108 kWh per year per refrigerator for a proposed Ontario-wide program. The Sacramento Municipal Utility District (SMUD) program measured the energy consumption of 79 refrigerators that had been removed as part of refrigerator decommissioning program, and found that an average of 150 kWh, or 6%, of annual energy savings were attributable to condenser coil cleaning (Bos, 1993). The Michigan Public Service Commission also conducted a program of removing second refrigerators in the mid 1980s, and estimated average savings of 544 kWh per year per refrigerator (Witte, 1993). This was about half what the engineering estimates had suggested.

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[30] Some modern refrigeration appliances use variable pumping rate compressors, which may slow down enough so as not to require a stop and start.

As the cost of monitoring appliances *in situ* is often too high, a large variety of simple criteria have been developed to evaluate the need for replacement. Cavallo and Mapp (2000) proposed an analytic method for determining if a refrigerator needs replacement, using energy and power monitoring over a two hour period, which is about the typical length of a house energy audit. Cavallo and Mapp (2003) tested a variety of criteria to determine how well they identified candidates for replacement, defined as having an actual energy consumption above a pre-determined level. The criteria were: 1) replace refrigerators with an annual energy rating above 849 kWh; 2) replace units manufactured before a particular year; 3) replace units with old-fashioned colours; 4) replace units that have a nameplate attached in an old-fashioned location; 5) remove all units with flexible walls containing fibreglass insulation; and 6) remove all models of brands that ceased production by the mid-1980s. Of these rules, rules 1 and 4 correctly identified a large proportion of replacement candidates. The other rules in isolation only identified a small fraction of the candidates. Using simple rules to determine which refrigerators should be replaced is difficult, but routine monitoring of removed appliances can assist in developing a more effective set of rules.

In situ monitoring of refrigerator energy use and temperatures was developed successfully for use in Michigan's Weatherization Assistance Program (WAP) (Knoll, 2003). Meters were developed to meet the monitoring requirements with a two hour monitoring protocol, and procedures developed for the monitoring and analysis. Protocols for deciding on replacement were developed, using the software *National Energy Audit Tool (NEAT)*, or *Replace?*, with additional criteria based on the monitored temperatures for health and safety reasons. The overall protocol gave the assessor confidence that they were correctly identifying refrigerators for replacement, and the savings to investment ratio of 2.9 was higher than the minimum required of 1.5.

Recycling of discarded refrigeration appliances is now commonplace in many countries. Dedicated recycling plants, such as the Universal-Querstromzerspaner supplied by German manufacturer MeWa Recycling Maschinen und Anlagenbau GmbH, are now available that can efficiently recycle large quantities of refrigeration appliances (up to 60 units per hour), and enable almost all the materials, including the foam blowing agent, to be recycled (see http://www.mewa-recycling.de/).

Whilst the proper disposal of discarded refrigeration appliances is becoming routine, it is arguable that many are being kept too long before disposal, resulting in excessive energy consumption during use, and the loss of refrigerant before recycling. Kim, Keoleian and Horrie (2006) showed that the optimal lifetime of refrigeration appliances ranged from 2-7 years for energy, and 2-11 years for Global Warming Potential, depending on the age of the refrigerator, but the minimal economic cost was at a lifetime of 18 years.

Even if refrigeration appliances operate properly for their entire life, early replacement may give lower economic cost, and less energy use. If they develop faults that are not rectified then there may be excessive energy wastage.

22.2 Appliance data

Refrigeration appliance data from approximately 400 HEEP houses was available. Of these, 25% had end-use monitoring of individual appliances, which usually included one or more refrigeration appliances.

Appliance power was monitored for 147 separate refrigeration appliances. The length of the monitoring period varied, from as little as one month (approximately) to up to one year, on a random basis. Two types of equipment were used (described in Section 1.1, Isaacs, Camilleri, French et al. 2006):

- Australian manufactured EUM transponders (using current transducers) with a nominal resolution of 1 W, and
- Siemens SA100 domestic tariff meters modified to have a resolution of approximately 10 pulses per Wh (1.6 pulses per W per 10 minutes).

Collected data is stored as 10 minute resolution time series. A typical example of the time series of a refrigeration appliance in normal operation is given in Figure 110. In this case, the compressor power is approximately 170 W, the off-cycle power consumption is about 15 W, and defrosting occurs about once every three days.

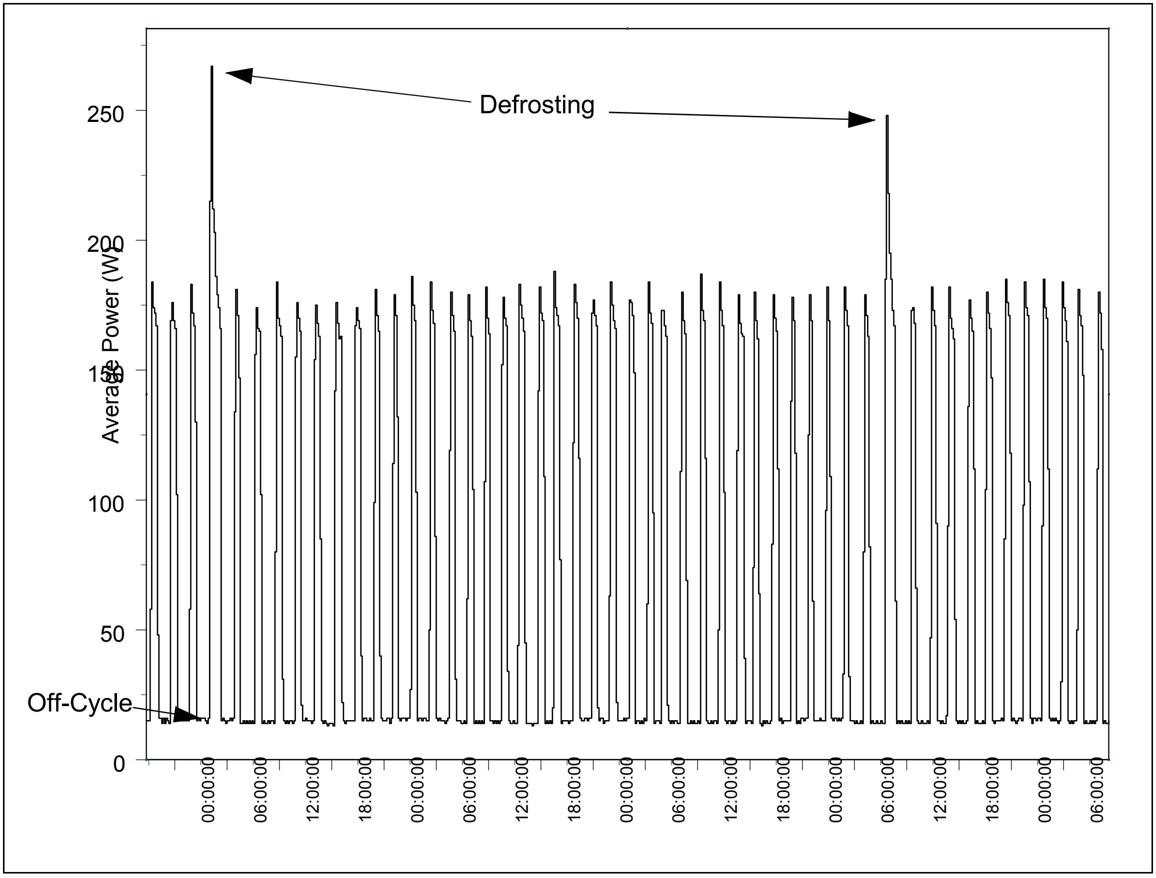

Figure 110: 10 minute time series of refrigeration appliance power

An example of a faulty freezer is given in Figure 111, in which the compressor stays on for long periods of time, and occasionally switches off. Some faulty refrigeration appliances never switch off.

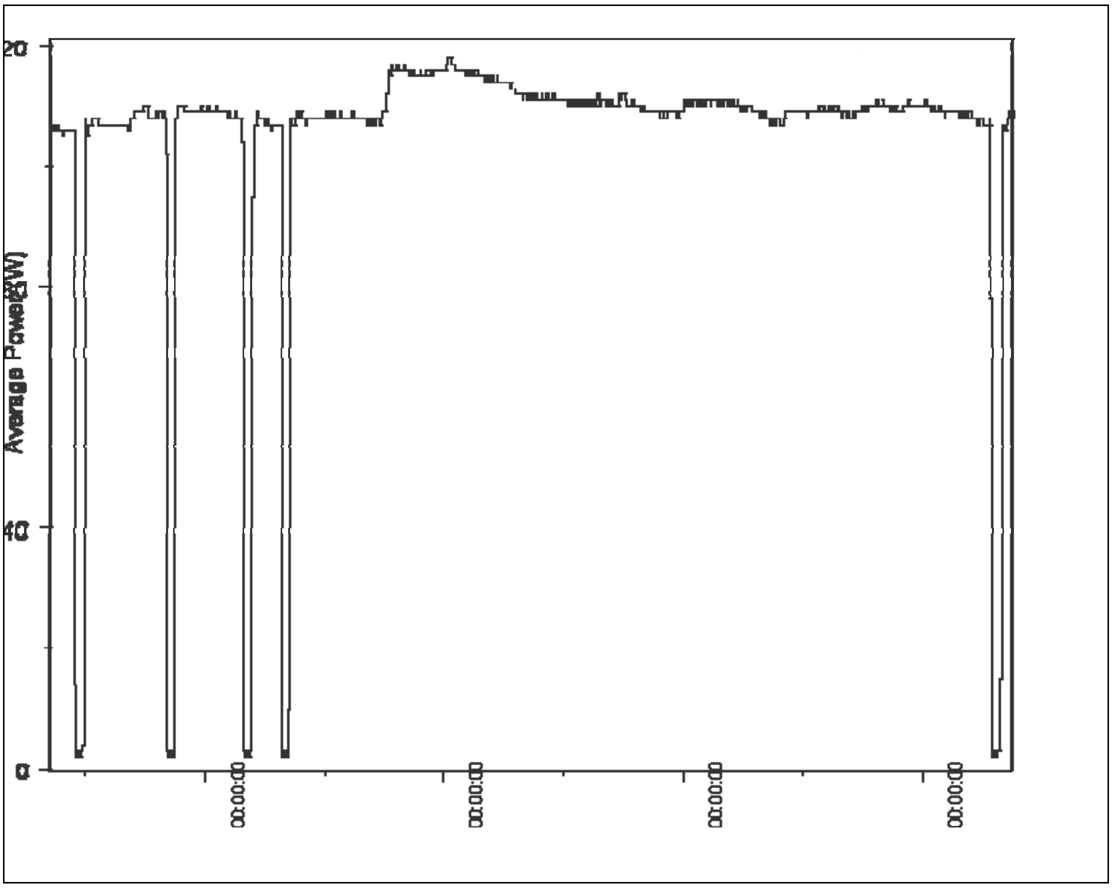

Figure 111: Faulty freezer – 10 minute time series

Some refrigeration appliances have a very short switching cycle, and if the off period is less than 20 minutes then the cycles cannot always be properly resolved at a 10 minute sampling interval. An example of such a time series is in Figure 112.

Since the length of the off-cycle is close to 10 minutes, its start and finish do not always coincide with the datalogger's 10 minute interval. This is a difficult situation to deal with, and three such cases were removed from the analysis due to this problem.

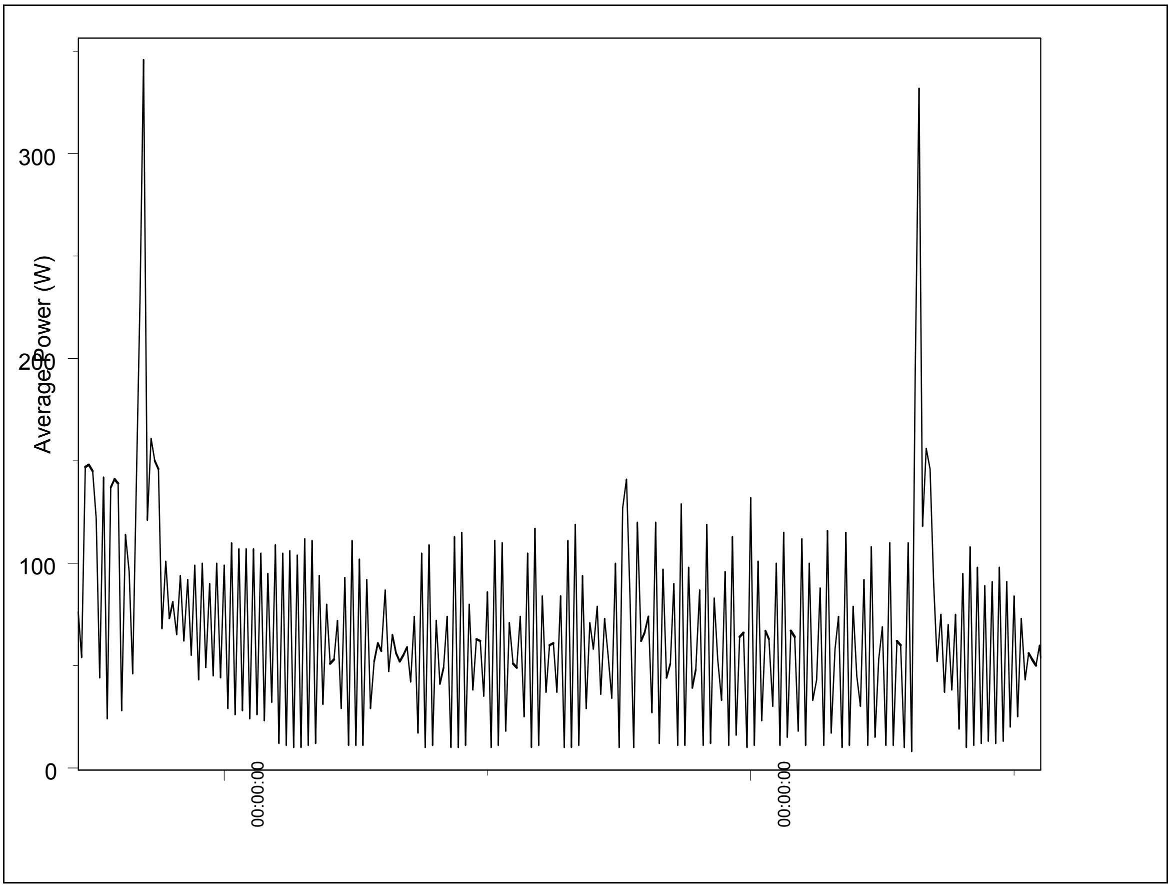

Figure 112: Fridge freezer 10 min time series – cycles <20 min but not faulty

22.3 Methodology

The method for deciding if a refrigeration appliance was faulty was to graph and visually inspect the data for signs of continuous compressor operation. All 147 monitored appliances were inspected and classed as either faulty, marginal, or normal, and this was used as the control data set for the testing and development of decision algorithms.

The algorithm of Cavallo and Mapp (2000) was initially tested, and adapted to be more suitable for the HEEP data. Modifications were needed as this algorithm estimates the duty cycle by comparing the average power over a two hour period to the average power when running (on-cycle power consumption). In contrast, HEEP measurements are the average power over a 10 minute interval taken over many weeks. The long-term average power consumption can be taken as the average power. However, as the start and end of a compressor on-cycle will not normally coincide with the start and end of an interval, the average power when running as recorded by the 10 minute time series will under-estimate the on-cycle power consumption compared to a two hour measurement. Observe in Figure 110 how the compressor power does not usually jump up from the off-cycle to the on-cycle power consumption, but has an intermediate step. The power consumption while the refrigerator is in the on-cycle can also be seen in this graph to vary from cycle to cycle – in this example the on-cycle power consumption is around 160 W.

To estimate the on-cycle power consumption, the intermediate steps in power consumption must be ignored, and some type of average of the observed on-cycles taken. To do this, the mode (statistical) of the refrigeration appliance power was calculated, ignoring the off-cycle mode. The refrigerator in Figure 110 has an on-cycle mode of 176 W and an off-cycle mode of 19 W.

Other modifications were needed for the algorithm of Cavallo and Mapp (2000), as many refrigeration appliances also have an off-cycle power consumption (e.g. fans, controllers etc) which needs to be estimated and subtracted from both the average and modal on-cycle power consumption. Cyclic defrost refrigerators normally power up a heater in the off-cycle – a heater that is not operating when the compressor is running. For some modern refrigeration appliances, particularly those with fans and micro-processor controls, the off-cycle power consumption can be tens of Watts, and if the off-cycle power consumption is not removed the refrigerator duty cycle would be overestimated.

Equation 22 gives the modified calculation for the duty cycle:

$$\text{Duty Cycle} = \left(\frac{\text{Average Power} - \text{Off-Cycle Power}}{\text{On-Cycle Power} - \text{Off-Cycle Power}} \right)$$

Equation 22

where the off-cycle power and on-cycle power are the mode estimated from the density distribution of 10 minute power consumptions.

22.4 Results

From the visual data inspection, 7% of refrigeration appliances were found to be faulty, and an additional 9% were marginal, showing faulty operation for short periods of time (days to weeks). The breakdown of the proportion of faulty appliances by type is given in Table 125. The sample and proportion of faults was not large enough to determine if there were differences in the proportions of faulty and marginal appliances by type. However, after combining groups, there is a significant difference between freezers and other types of refrigeration appliences in the overall proportion of faults (faulty or marginal), with freezers being more likely to be faulty (Chi-square test, $Chi^2 = 4.54$, DF= 1, p=0.033).

Type	*Count*	*Faulty*	*Marginal*	*Sum*	*Faulty*	*Marginal*	*Sum*
Freezers	60	5	9	14	8%	15%	23%
Fridge freezers	70	3	5	8	4%	7%	11%
Fridges	17	1	0	1	6%	0%	6%

Table 125: Breakdown of faulty appliances by type

The age of the faulty refrigeration appliances is based on sparse data, with only 10 out of the 18 faulty and marginally faulty refrigeration appliances able to be dated accurately. Despite these limitations, the data shows a statistically significant variation in the proportion of faulty appliances by decade, with approximately 67% of the 1960s appliances being faulty (note that this proportion has a very large statistical uncertainty). This supports the commonly held idea that the older the refrigeration appliance, the more likely it is to be faulty.

Decade	*Working*	*Faulty*	*Total*	*% Faulty*
1960s	1	2	3	67%
1970s	10	1	11	9%
1980s	20	1	21	5%
1990s	31	6	37	16%
2000s	14	0	14	0%

Table 126: Breakdown of refrigeration appliances by decade

Six refrigeration appliances (12%) from the 1990s were faulty, of which three were running continuously and three were marginal. This is alarming, as modern refrigeration appliances are expected to have a working life of more than 10 years. Perhaps the change to non-CFC refrigerants in 1994 affected their reliability. No appliances from the 2000 decade were faulty (these were less than 5 years old at the time of monitoring).

A Chi-squared test for a difference of proportions shows that the increase in faults for older appliances is statistically significant. (5-sample test for equality of proportions without continuity correction Chi-square = 12.5, DF = 4, p-value = 0.014.)

22.5 Testing Cavallo and Mapp algorithm

The algorithm of Cavallo and Mapp (2000) for deciding whether a refrigeration appliance is due for replacement was applied to the refrigeration appliance data to compare with the visual inspection. The parts of the algorithm relevant to New Zealand refrigeration appliances are:

1. wattage when running >250 W
2. kWh usage in one hour >0.15 kWh (two hour test)
3. kWh usage in one hour divided by kW when running >0.7 (two hour test)
4. any model with an anti-sweat device (5 to 40 W when not running)
5. runs continuously for more than one hour.

The anti-sweat device criterion is not relevant for most New Zealand refrigeration appliances. Many models have fans or electronic controls which give an off-cycle power consumption of, typically, 5-20 W. In addition, many New Zealand refrigerators have a butter conditioner, which is a small compartment (about 1 litre), that has a small 10-15 W heater that runs continuously to keep butter soft. This off-cycle power consumption was subtracted from the net power consumption of each refrigeration appliance.

The exact algorithm tested was: replace if:

1. wattage when running >250 W, or
2. average wattage >150 W, or
3. average wattage divided by average wattage when running >0.7.

All wattages are exclusive of the off-cycle power consumption. The performance of this modified algorithm is given in Table 127:

Correctly identified faulty	15
Correctly identified OK	118
Incorrectly identified faulty	6
Incorrectly identified OK	8

Table 127: Performance of algorithm at threshold of 0.7

The faulty indication threshold of a >0.7 duty cycle falsely identified eight refrigeration appliances as faulty, and six as not faulty. On inspection, the duty cycles of the faulty appliances (compressor running continuously for long periods) were all 0.9 or greater. Only one refrigeration appliance with a calculated duty cycle >0.9 was not in fact faulty, but had a very short compressor cycle that could not be resolved at the 10 minute time resolution.

It is worth noting, though, that although a duty threshold of 0.9 (Table 4) was better able to correctly identify faulty appliances and leave out non-faulty ones, it failed to detect many marginal appliances.

Correctly identified faulty	9
Correctly identified OK	123
Incorrectly identified faulty	1
Incorrectly identified OK	14

Table 128: Performance of algorithm at threshold of 0.9

Monitoring refrigeration appliances is the most reliable way of determining if they are faulty. However as an alternative, a simple check test could be applied. If the occupant was asked to check the appliance, say, five times over a day or two and record if the compressor was running or not, then it is highly likely that the compressor is running continuously if it was always found on.

The latest models of refrigeration appliances sometimes have sophisticated electronic controls, fan forced compartments, and many other control features designed to improve performance. Monitoring and testing appliances with these types of controls may cause problems in the future, if for example it is in a specific mode that is not typical of normal energy consumption, or if the loads from fans and other controls[31] are high. The future performance of the measurement algorithms will have to be tested against the ever changing appliances.

22.6 Energy waste from faulty refrigeration appliances

When a refrigeration appliance is faulty, the compressor stays on for longer than it should, perhaps continuously. By comparing a normal duty cycle with the faulty duty cycle the energy wastage could be estimated. However, most of the faulty refrigeration appliances do not have a period of normal operation from which a normal duty-cycle could be observed. To establish a normal duty cycle, the average duty cycles of all the normally functioning appliances were calculated. They are 47%±2% for all non-faulty refrigeration appliances, or by appliance type 48%±4% for freezers, 48%±4% for fridge freezers, and 40%±10% for fridges. The variations between appliance types are not statistically significant. Duty cycles average 47%, so a faulty refrigeration appliance would use about double the normal energy for refrigeration (excluding off-cycle power consumption).

On average, the normally working refrigeration appliances averaged (63±2) W, the marginal ones (101±7) W and the faulty ones (108±15) W. The faulty and marginal refrigeration appliances used on average (42±17) W more than they would if operating properly, which would cost the owners about $56 per year in electricity. As a national average, the excess power consumption would be about 105 kWh per household per year or 17 MW of continuous load nationwide. This is a sizable amount, about 1% of household energy consumption.

This excess energy consumption is on average about 11% of household refrigeration energy consumption.

If we assume that the faulty appliances are replaced with modern ones that use 50% of the energy of the old ones, then there would be savings of roughly 35 W per appliance, which would be about an additional 20 MW of load nationally. If we assume that half of the appliances are disposed of and not replaced, then the savings, including reductions for units that are replaced, would be about 53 W per appliance, or about 310 kWh per household per

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[31] Some new appliances have network or text message connections, and some even have built in screens for watching TV or viewing recipes. Trying to deal with these as part of an audit may become impractical. Some may self-diagnose problems.

year, for nationwide savings of about 30 MW. The total net savings of a nationwide program that withdrew faulty appliances, and replaced half of them with modern ones, would be about 50 MW of continuous load, which is about 3% of household energy consumption.

22.7 Implications for energy savings programs

Clearly, identifying and repairing or decommissioning faulty refrigeration appliances should be part of any household energy savings plan. One in every six (16%) New Zealand refrigeration appliances are faulty or marginally faulty. This is higher than it should be, and it would suggest that households are keeping refrigeration appliances too long before disposal.

Many energy savings programs are targeted at low-income households. Whilst these households may be more likely to have older, less efficient appliances, faulty refrigeration appliances appear to be more widely distributed. Often, the faulty appliance was a secondary appliance tucked away in a garage (the old beer fridge) or a utility room. It appears that in many households when a main refrigeration appliance is replaced the old one does not leave the house, and the household ends up with two appliances instead of one. A more general practice of recovering old refrigerators when new ones are purchased might have merit, as could other measures such as a ban on the resale of old refrigerators.

22.8 Greenhouse gas emissions

Refrigeration appliances manufactured before 1994 were charged with CFCs, which are both highly potent greenhouse gases and ozone-depleting substances. If refrigeration appliances are left to fail completely before disposal, the refrigerant may leak before it can be safely recovered. From the HEEP age estimates, about 60% of refrigeration appliances were made before 1994, so roughly 1.5 million still-in-use refrigeration appliances have CFCs. As a rough estimate, based on 100 gm of CFC-12 per appliance, there is about 150,000 kg (150 tonnes) of CFC-12 still stored in refrigeration appliances. With a global warming potential of about 10,600 times that of CO_2, this is equivalent to 1,590 kt CO_2. At the peak, New Zealand used about 2,500 tonnes of CFC-12 Ozone Depleting Potential (ODP) equivalent per week – 150 tonnes is about three weeks of peak use.

Recovery of CFCs refrigerants from refrigeration appliances is poor. Refrigerant appears to be lost either as the unit fails, during storage before disposal (corrosion of tubing), or from damage during removal and transport, especially for units that had exposed rear coils. The refrigerant is often lost completely before recycling can take place. At this stage, it is impossible to know the proportion of losses at each stage in New Zealand. In addition, foam use in pre-late-1994 appliances contained CFCs. Recovery of the CFCs from the insulation (and the HCFCs from the insulation of some imported 1994 to 2002 refrigerators) is currently not done in New Zealand.

22.9 Discussion and conclusions

In New Zealand, approximately 7% of household refrigeration appliances are faulty, and a further 9% operate marginally. Their excess energy consumption is estimated at 105 kWh p.a. per household, which is about 11% of all household refrigeration energy consumption, and about 1% of household electricity consumption. The potential for energy savings from decommissioning these refrigeration appliances may be large enough to support a nationwide decommissioning program. Energy savings from the removal and/or new replacement of all faulty refrigeration appliances would total about 310 kWh p.a. per household, which is about 1/3 of refrigeration energy consumption, or about 3% of household energy consumption.

Faulty refrigeration appliances can be identified by unusually long periods (weeks or months) where the compressor is on continuously, and can easily be identified by inspection or short-term monitoring. Marginally faulty refrigeration appliances have short periods (a few days or weeks) when the compressor does not switch off, and are less likely to be identified. The algorithm of Cavallo and Mapp (2000) has been adapted to New Zealand refrigeration appliances, tested and found to correctly identify about 2/3 of faulty refrigeration appliances, with 1/3 false positives and 1/3 false negatives. A higher threshold of 0.9 gives almost no false positives, but still only identifies 2/3 of the faulty appliances as it misses many of the marginal ones.

Older refrigeration appliances appear to be more likely to be faulty, with two-thirds of 1960s refrigeration appliances being faulty (note that this has a large uncertainty).

The proportion of faulty refrigeration appliances in other countries is not known, and we can only speculate that in a country with a similar age distribution of appliances the proportion that is faulty would be similar. It would therefore be worthwhile to investigate the potential for energy savings and CFC recovery as part of energy-efficiency programs.

It is also worth noting that the energy savings from replacement of older refrigeration appliances with modern appliances will benefit from the improved energy performance of newer appliances. Figure 113 shows that the sales-weighted energy use of new fridge freezers in Australasia has reduced over time, benefiting first from the energy labelling requirements and more recently from minimum energy performance standards (MEPS). Over the past 26 years, the sales-weight average energy use has fallen by two thirds (Pers. Com. Lloyd Harrington; Energy Efficient Strategies 2006).

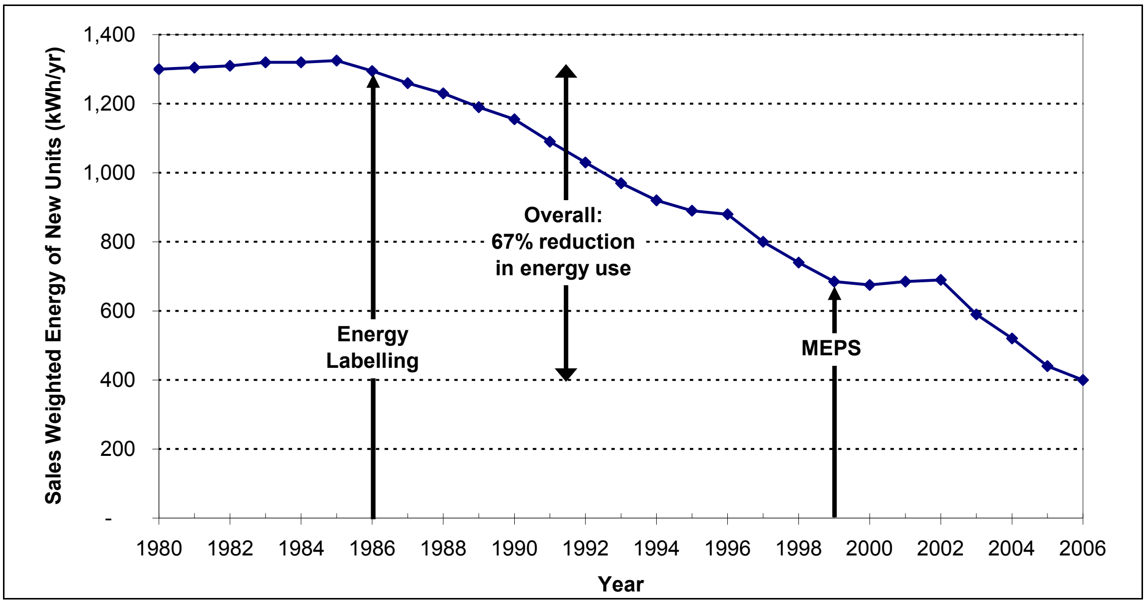

Figure 113: Energy use of new frost-free fridge freezers 1980-2006

23. LOAD FACTORS AND REACTIVE POWER

This section addresses both the load factors and reactive power of nine HEEP houses. Load factors examine at the highest electric load compared to the averaged load of a house over the monitoring period, while power factors explore the relationship between the measured real and reactive electric power demand.

Load factor analysis was first examined in the HEEP Year 5 report (Stoecklein et al., 2001) while power factors were considered in Section 10 of the Year 10 report (Isaacs et al., 2006)

23.1 Load factors

Load factors are a commonly used way to describe how well balanced a load profile is over the year. A load factor is defined as the mean power during the monitoring period – generally one year – divided by the maximum power during this period.

Load factors are generally calculated for the average load of large groups of electricity users. Because of this averaging effect, the group profiles are naturally smoothened. This approach is not quite suitable when analysing individual households, because load profiles in individual households have much larger fluctuations than the load profiles of consumer groups. Using the maximum load of an individual household for determining its load factor would distort the result because this maximum load may be a one-off occurrence of extraordinary circumstance and therefore very untypical for the rest of the monitoring period.

Therefore, a slightly modified calculation method had to be used: instead of determining the peak load for the whole monitoring period, the time-series was first converted into twelve 24-hour average load profiles, one profile for each month. Then the maximum load of these profiles was determined and used in the load factor calculation.

Figure 114 shows the load factors for all monitored houses in Hamilton, Wanganui and Wellington. The graph shows that there is no significant difference between the mean load factors for the pensioner households and the other Hamilton households, which were randomly selected (p-value = 0.5). This result suggests that the load patterns between households occupied by pensioner and by non-pensioners were not significantly different in their peak load to base load demands.

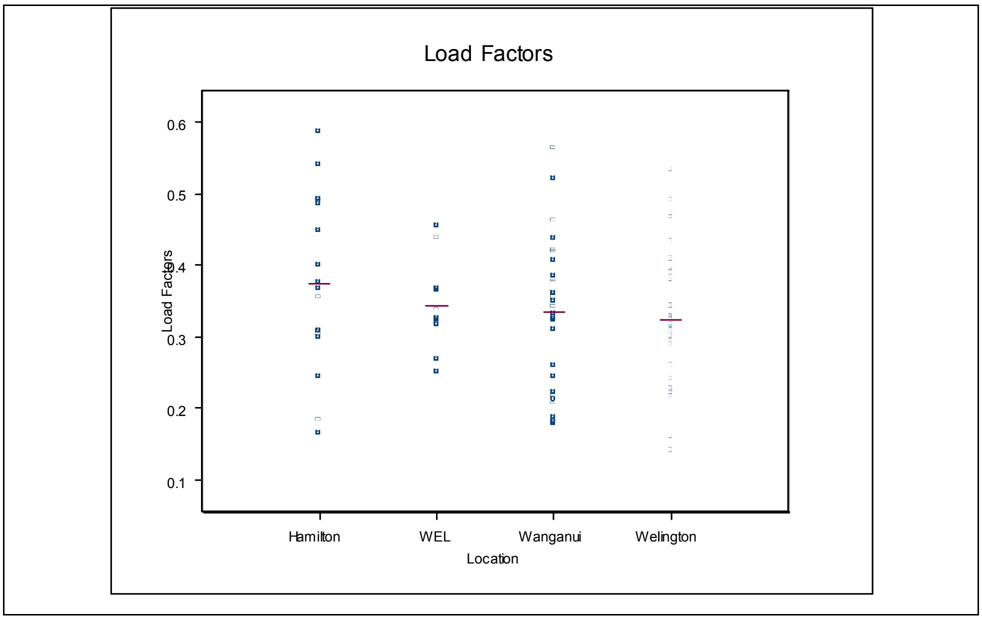

Figure 114: **Power factors for monitored houses - Hamilton, Wanganui and Wellington**

Note to Figure 114: 'WEL' houses are a subset of townhouses in Hamilton, which are mostly occupied by superannuitants. Horizontal lines indicate the mean.

To gain a more detailed understanding of the peak to average load relationship, the load curves for the monitored houses were calculated using the time-series of total electricity consumption with a 1-hour resolution. The calculated load curves were then averaged across all households in the same population centre. Figure 115 indicates that the load curves for households in Hamilton have a steeper drop than the ones for other centres. In particular, the households which consist mainly of superannuitants ('WEL' households) show load curves which suggest that their electricity consumption patterns contain fewer spikes than the patterns in other households.

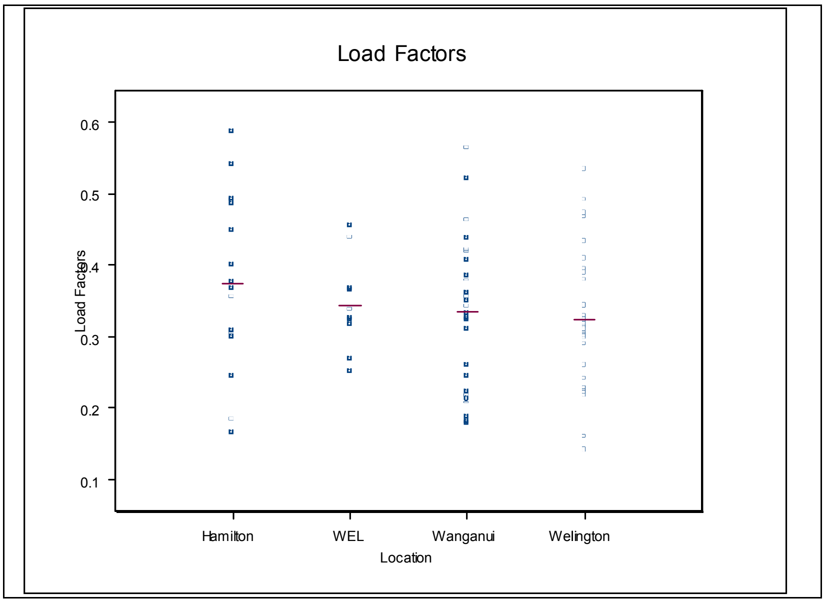

Figure 115: Load curves for different HEEP locations

23.2 Reactive power

The load on an electricity network grid is made up of both resistive (real power kW) and inductive or capacitive (reactive power kVAr) loads. The total burden (apparent power kVA) on the network is the vector sum of both the real and reactive components. The ratio of the real load to the total burden is called the ‘power factor’ and will be 1.0 for a purely resistive load (like the heating element in a hot water cylinder or an incandescent light bulb) and 0 for a purely inductive or capacitive load. Household appliances which contain motors (e.g. a vacuum cleaner) will have an increased inductive load and a low power factor.

AC power is transmitted with the least losses if the current is undistorted and exactly synchronised with the voltage. The lower the power factor, the more current is required to deliver the same amount of power. The overall power factor for a household will depend on how many reactive and resistive appliances are used within the house and when, and for how long, these appliances are used. These factors can vary considerably between households so the variation of the power factor between households will be of interest.

During years 7, 8 and 9 of HEEP,, electricity use in three houses was monitored with equipment (TML meters)[32] capable of measuring both real and reactive power and consequently reporting household power factors. This equipment is described in the HEEP Year 6 report (Section 4.2, Isaacs et al 2002) which also provides some results from an initial examination of one of these (House 1) installations (Section 7.2, Isaacs et al 2002).

The households into which the TML meters were installed were chosen for a number of practical reasons (such as space around existing metering etc), and preference was given to households with electricity being a major fuel use in the house. As the TML metered households were not randomly selected this analysis is exploratory of the power factor issues and should not be regarded as representative. This study, however, provides an indication of the variation of power factors between different households and may be useful to determine an appropriate sample size for a more detailed (statistically representative) study of the issues involved.

In 2002 the TML meters were installed into three households in Auckland and the North Shore. In 2003 the equipment was relocated to Whangarei, but due to a monitoring problem data was only available from two of these households. For the final year (2004) of monitoring, the equipment monitored three Thames households. During this final year, the occupants in one of these houses (House 7) moved out and were immediately replaced with new occupants. There was a change in how much reactive power was used with this change of occupants, so the data from the two households (denoted as House 7a and House 7b) is analysed separately.

The households into which the TML meters were installed varied. The households ranged in size from 1-5 people. The floor area of the houses ranged from 56-172 m^2, averaging 106 m^2. Household incomes varied with the equivalised income (see Section 12.2) and differed by a factor of more than seven from lowest to highest.

An important source of inductive load within a household is from the operation of electrical motors in appliances. Refrigeration appliances are typically always switched on and the compressor motors within these appliances are frequently running. For the nine households examined, four had two refrigeration appliances (two had fridge freezers with a separate freezer and the other two had refrigerators with a separate freezer). The remaining five households had a single refrigeration appliance, being a fridge freezer for four of the

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[32] Now renamed Energy Intellect – see www.energyintellect.com.

households and a single door refrigerator for the remaining household. The ownership of particular appliances for each household is shown in Table 129.

House	1	2	3	4	5	6	7a	8	7b
Refrigerator								1	1
Fridge freezer	1	1		1	1	1	1		
Freezer	1		1			1			1

Table 129: Ownership of refrigeration appliances

Other frequently operated motorised appliances that may be contributing to the reactive load by the household could include clothes dryers, dishwashers, vacuum cleaners, sewing machines, cooling fans, extractor fans, dehumidifiers, air conditioners, fan heaters, electric garden tools and power tools. The number of these types of appliances varied within the households examined; four households had clothes dryers and four had dishwashers, and only one household had a dehumidifier.

Lighting was predominantly incandescent (resistive), with all of the houses having a number of incandescent fixtures. Only two households had compact fluorescent lighting (inductive, not electronic ballasts), but these households had only one CFL fitting each. Two other households had fluorescent strip lighting (inductive), one of which also contained a number of halogen lights (resistive).

Heating methods within the selected households varied and included two households with woodburners, two households with portable LPG cabinet heaters, one household with reticulated natural gas and one household with an air conditioner.

With one exception, all of the households used electricity for their water heating and cooking. The remaining house had a reticulated gas supply which provided water heating, cooking hobs and gas heating.

In addition to motors and fluorescent lighting, many electronic devices can provide a poor power factor, although good design can minimise this effect.

23.3 Measured reactive power and power factor

Over the course of a measurement period within an actual household, the real power and reactive power will vary and consequently the apparent power and power factor will also vary. The magnitude of the real power is generally much greater than the magnitude of the reactive power.

Figure 116 shows a time-series graph of the daily average reactive power, real power and power factor for one house. It can be seen that for this household there was a seasonal variation in power factor and that the high power factor during the winter months coincided with high values of real power. The reactive power was largely constant throughout the year, although seven out of the nine households (including the house in Figure 116) had some reduction during the winter.

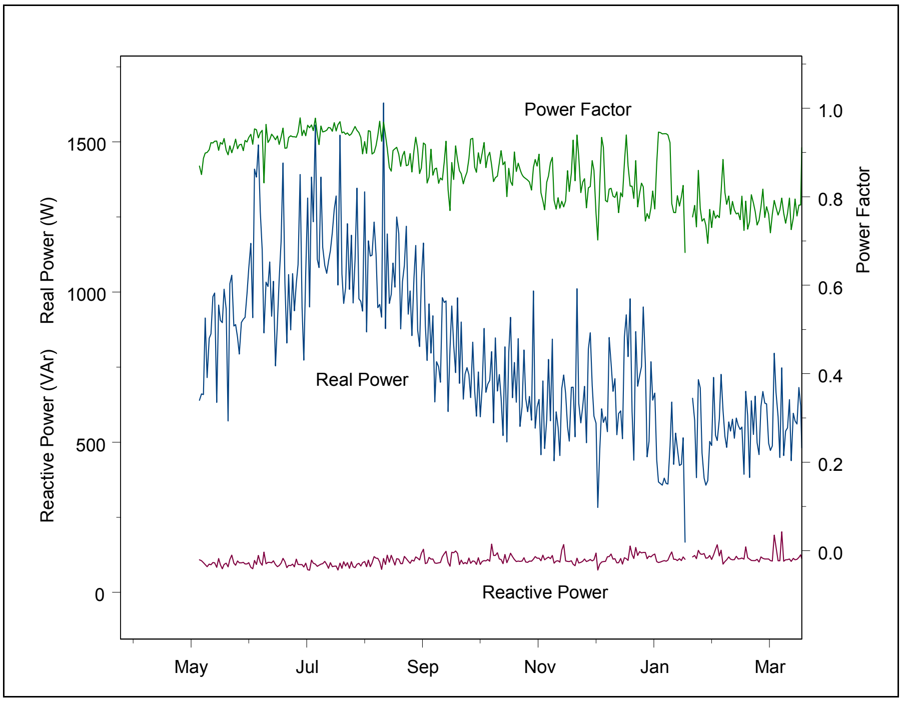

Figure 116: Household daily average real and reactive power and power factor

Figure 117 provides a series of histograms of the 10 minute power factors for each household. Overall, the mean power factor varied from 0.76 (for House 1) to 0.97 (for House 2). The mean of the power factor for the nine households was 0.86.

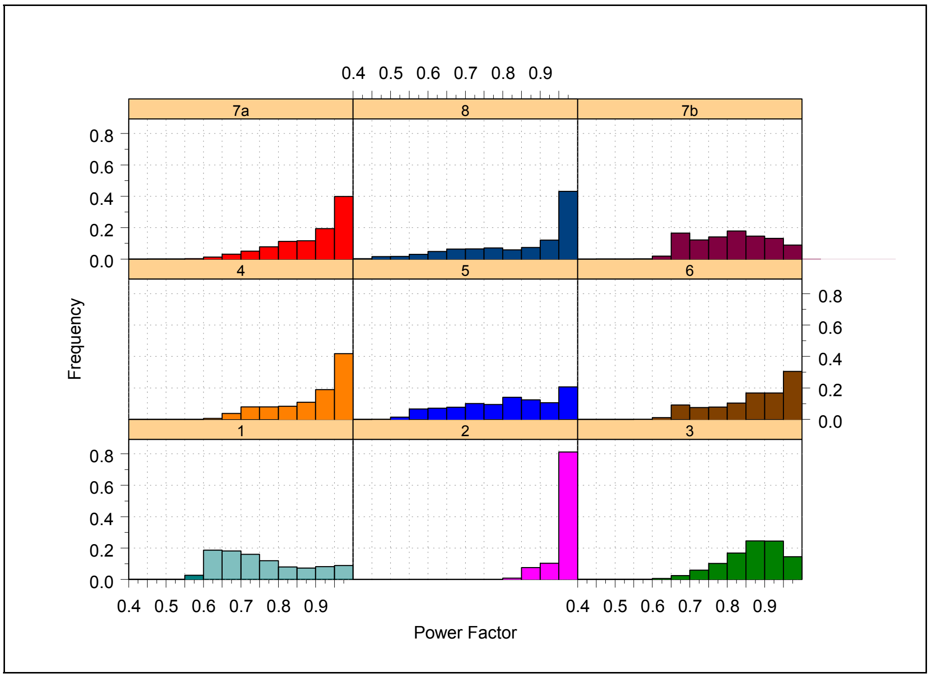

Figure 117: Histograms of the 10 minute power factors by household

Figure 118 compares the mean real power and the mean reactive power for each household. The average power factor for each of the houses is also shown in brackets after the house designator. It should be noted that the Y-axis (the reactive power) has been exaggerated to allow the spread of the reactive data to be better examined.

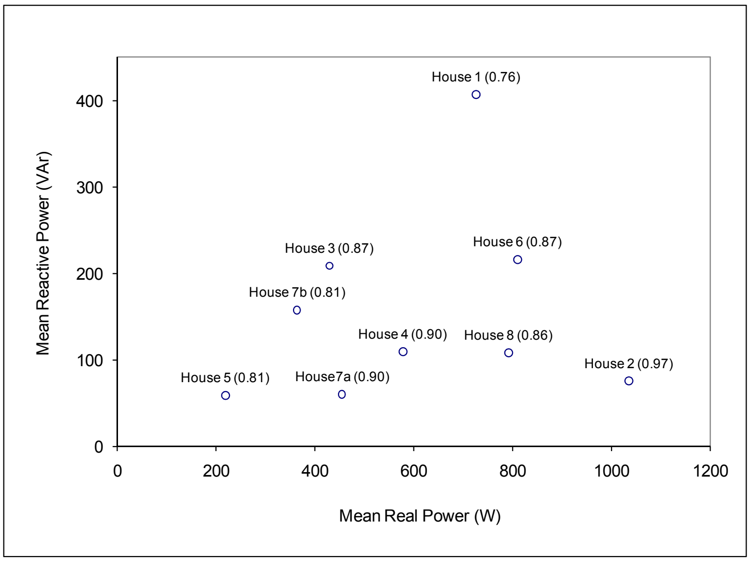

Figure 118:Mean real and reactive components for each household

Note: mean power factor shown in brackets.

The relationship between the real and reactive power is further examined for each individual household in Figure 119, which provides scatter plots of the 10 minute data of the real and reactive power plotted against one another. Again the Y-axis (the reactive power) has been exaggerated, this time to magnify any trend of increasing reactive load with increasing resistive (real) load.

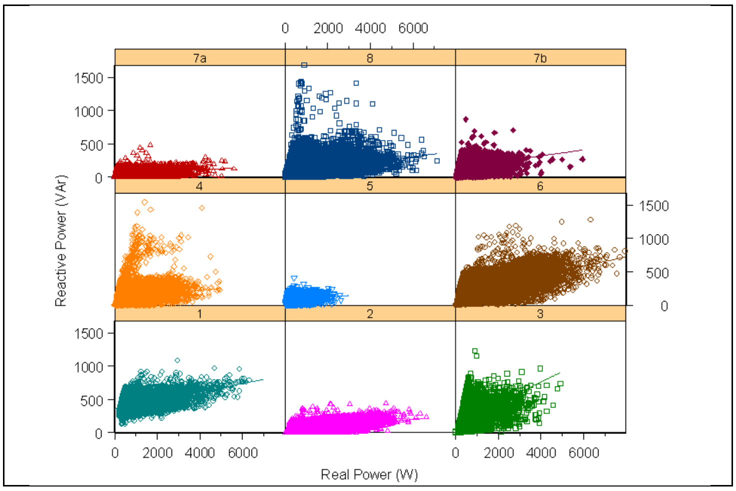

Figure 119: Real vs. reactive power by household

House 1 (shown in the bottom left hand corner of Figure 119) had the lowest mean power factor of all the households examined (0.76) and was the only household which appeared to have a reactive power and real power offset. The minimum real power in any 10 minute period is 222 W, with the minimum reactive power being 120 VAr. The minimum apparent power is 344 VA. It is probable that a constant load (which had a reactive component) was running all the time. HEEP has previously identified old freezers as frequently being faulty and running all the time (Isaacs et al 2004). House 1 had an old freezer in the garage and this may have been a contributing cause to the high reactive energy use in this household.

Figure 120 shows a time-series plot of the real power, reactive power and power factor for one particular day in summer for House 1. Figure 121 shows the same variables for another household (House 6). Both House 1 and House 6 had one combination fridge freezer as well as a separate freezer. The background pattern of the reactive power for House 1 was a regular switching event with a constant offset. This is consistent with a fridge freezer operating correctly with a faulty freezer operating continuously. The background pattern of the reactive power for House 6 differs in that there were times when there were high peaks and zero usage (both appliances operating at the same time) and times when there were smaller peaks and non-zero usage (appliances operating at overlapping times), which is consistent with both appliances' cycling operating at slightly different frequencies.

To examine the costs of running this constant load in House 1, a dataset was constructed that extracted the bottom 5% of the data (based on the total apparent energy). This data set had a mean real energy use of approximately 2300 kWh per year, a mean reactive energy use of 2500 kVArh, an overall mean apparent energy use of 3400 kVAh, and a mean power factor of 0.67. Taking the weighted average retail electricity cost from incumbent retailers as at 15 May 2007 as 21 cents per kWh, this constant load would not only cost the householder approximately $480 to run but would also add a considerable (and possibly avoidable) reactive load to the electricity network. This in turn adds costs to the distribution, transmission and generation systems.

The power factor of this large household (House 1) was degraded by the inclusion of a number of reactive motorised appliances e.g. clothes dryer, dishwasher, as well as the omission of resistive appliances (such as heaters, hot water cylinders, cooking hobs), due to these services being supplied by reticulated gas.

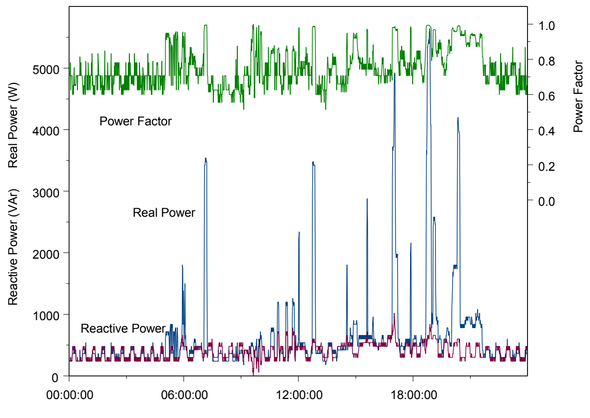

Figure 120: House 1 summer day – real & reactive power, power factor

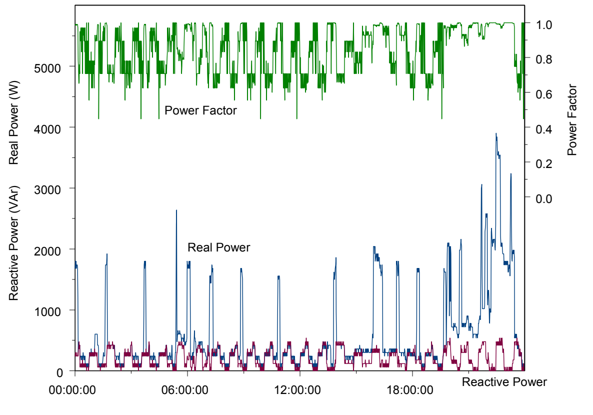

Figure 121: House 6 summer day – real & reactive power, power factor

At the other extreme from House 1 is House 2 which had a power factor of 0.97. This was a single-occupant household with a single modern fridge freezer (made in 2001), with no clothes dryer or dishwasher. Heating was provided by a number of portable electric heaters with no fan heaters, air-conditioners or dehumidifiers.

The monitoring for the TML metered households was undertaken at household level with no specific appliance monitoring undertaken. It may be beneficial in future studies to also undertake appliance monitoring to assist with determining which appliances most contribute to poor power factors at a household level.

Figure 122 provides average time of day profiles for the reactive power, real power and power factors for each household. Over the course of a day, the reactive power has a flatter profile than the real power, suggesting that fixed (permanently operating) loads made up a sizeable proportion of the reactive energy consumption. These fixed loads could be made up from appliances left in their standby mode and other appliances that are left permanently on.

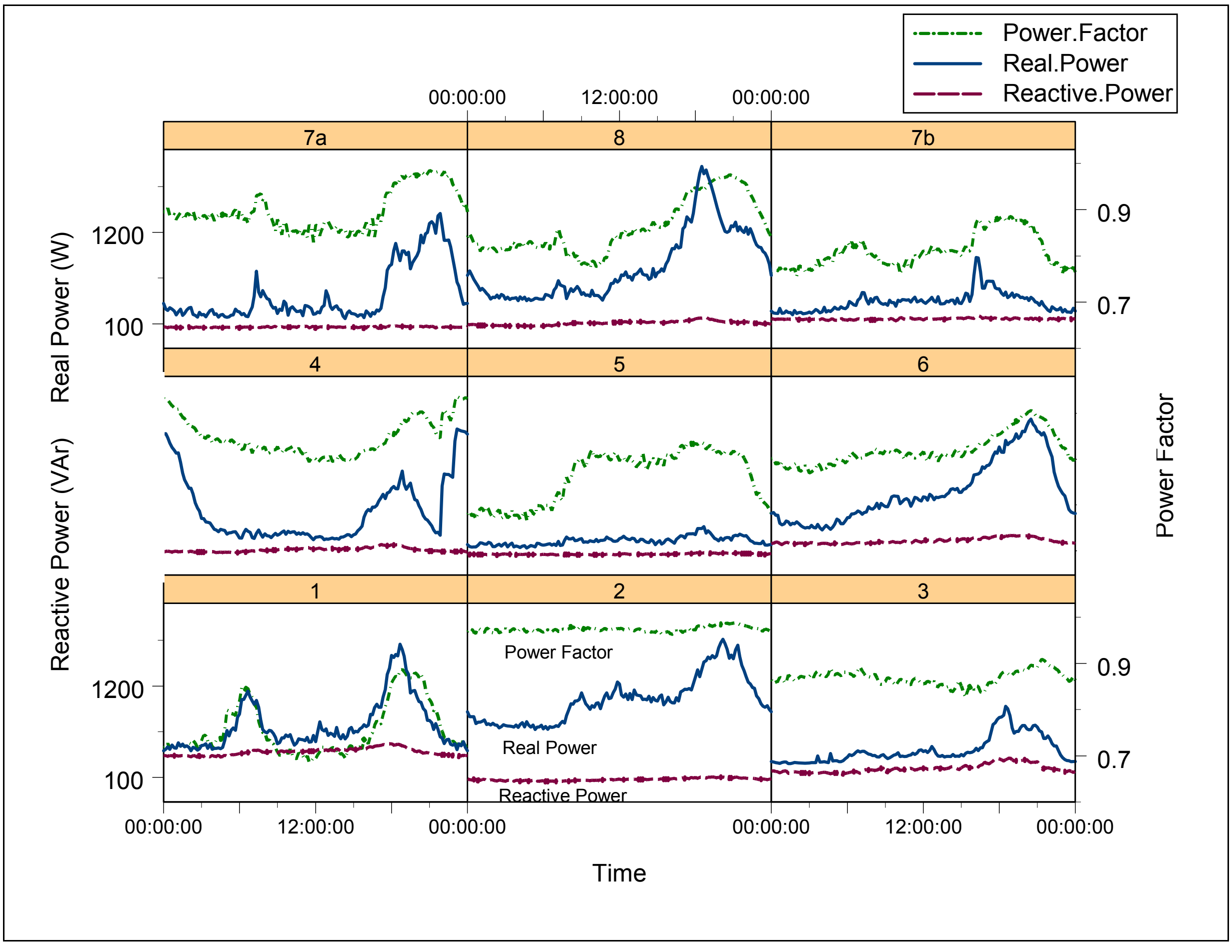

Figure 122: Average daily profiles by house – real and reactive power, power factor

Table 130 provides an estimate of the reactive energy from the appliances that are permanently on. This estimate has been constructed by taking the minimum value of the reactive energy profile as an estimate of the constant reactive load along with an estimate of the varying reactive load (the average difference of the reactive energy profile from this constant reactive baseload).

House 1	House 2	House 3	House 4	House 5	House 6	House 7a	House 8	House 7b
85%	70%	70%	67%	77%	79%	72%	63%	86%

Table 130: Average fraction of reactive energy from constant load

The average daily profiles of the power factor are also shown in Figure 122, and are frequently of a similar shape to that of the real power. However, they appear to have broader peaks than is the case for the real power.

24. DOMESTIC HOT WATER

24.1 Introduction

> *Men have gone to the moon and marvelled, but no greater event occurred on this earth than the abundance of soap and the unheralded arrival of hot and cold water by the turning of a tap. It is a gift of my lifetime, as is the leisure to use it. A rocket to the moon put millions of miles on to exploration potential; but hygiene – made possible by instant hot and cold water – probably doubled our life span.*
>
> *(John A. Lee, Early Days in New Zealand)*

Today, the provision of hot running water is considered a fundamental household requirement, yet only it is only since the 1960s that the majority of New Zealand houses have had an on-demand hot water supply.

The energy used by hot water systems relates to two key performance issues:

- **technical** – the system's thermal efficiency, which is largely under the control of the:
    - cylinder manufacturer (e.g. cylinder insulation, appliance efficiency, type of thermostat etc)
    - designer (e.g. type of system, distance to principal use, size of cylinder, size of 'element', shower mixer, shower head etc)
    - installer (e.g. pipe insulation, type of pipe, quality of installation, etc)
- **behavioural** – the usage of hot water, which is primarily driven by the users, e.g. thermostat setting, length of use, type of use (showers, baths, washing etc), time-of-day use etc.

HEEP has been concerned with separating these performance issues and investigating their relative importance in determining not only water energy use, but also their relevance to hot water use in specific appliances and hot water safety.

This section reviews the history of the provision of hot water in New Zealand homes, and makes comparisons with the current situation based on the results of HEEP. Note that not all households or hot water systems had all data available for all analyses. This may cause small variations in the total number of hot water systems between tables.

24.2 Hot water today

Today nearly every dwelling in New Zealand has hot water available on demand. This is a comparatively recent development, so the energy and service implications have not been investigated. The HEEP data provides a basis for such a study.

The majority of hot water systems are electric, with a small proportion fuelled by natural gas or LPG. Table 131 provides summary information for the four types of hot water systems monitored by HEEP: electric storage, electric night rate, natural gas storage and natural gas instantaneous. The error estimates provided in Table 131 are the estimates of the population standard error in the mean. 'Average cylinder temperature' is the average temperature of the water in the cylinder, taking account of how long it takes to heat water up from cold. Energy use is gross – i.e. as measured by the gas or electricity meter.

All HEEP DHW for which data is available	Electric Storage [*]	Electric Night Rate	Natural Gas Storage	Natural Gas Instant
Number of houses in sample	346	16	27	16
Age (years)	19.6 ± 0.8	13.9 ± 2.3	12.2 ± 1.7	3.5 ± 0.5
Cylinder volume (l)	157 ± 2	214 ± 13	152 ± 8	107 ± 73
Element size (kW equivalent)	2.2 ± 0.05	2.5 ± 0.3	7.3 ± 0.2	23.7 ± 2.5
Thermostat setting (°C) (as read)	60 ± 0.5	63 ± 2	64 ± 2	47 ± 4
Measured tap temperature (°C)	63.2 ± 0.6	66.8 ± 2.4	59.2 ± 1.4	51.5 ± 2.9
Average cylinder temperature (°C)	61.3 ± 0.6	68.8 ± 2.4	57.6 ± 1.5	
Ambient temperature (°C) [+]	18.1 ± 0.2	19.6 ± 1.2	18.4 ± 0.7	19.6 ± 0.2
Standing loss (kWh/day)	2.4 ± 0.1	2.6 ± 0.3	4.2 ± 0.2	
Used hot water energy (kWh/day)	4.9 ± 0.2	4 ± 0.6	11.4 ± 1.2	8.8 ± 2.3

Table 131: Hot water cylinder characteristics by type

Notes: [*] includes electric systems with solid fuel, solar or other supplementary fuels
[+] estimated average temperature around the hot water cylinder

For the purposes of analysis reported here, some of the strata were combined into Auckland, Hamilton/Tauranga and Dunedin/Invercargill urban areas. The clusters (rest of New Zealand) were split into 'warm' and 'cool' clusters, with the warm clusters those areas where the annual Heating Degree Days for the period May to August are less than or equal to 620 (see Stoecklein and Bassett 1999).

Table 187 lists the annual hot water gross energy (kWh) use and standard error per house by fuel and region. Note that although fuel oil is not separately included due to the small HEEP sample size it is included in the 'All fuels' summary column (Isaacs et al. 2006). This table covers all cylinder sizes and types for each fuel e.g. electric storage cylinders ranging from 15 litres to 315 litres. Table 187 therefore cannot be used to compare the performance of the different fuels – later tables (e.g. Table 142) provide information on specific fuel and cylinder sizes.

Location	All fuels	SE	Electricity	SE	Gas	SE	Solid fuel	SE
Overall	**3,260**	**100**	**2,440**	**80**	**660**	**90**	**150**	**40**
Auckland	3,580	200	2,310	180	1,270	260	-	-
Hamilton/Tauranga	3,390	530	2,590	590	660	320	140	60
Wellington	4,610	420	2,350	300	2,240	550	30	20
Christchurch	2,960	210	2,710	210	140	140	110	40
Dunedin/Invercargill	3,100	280	2,840	310	-	-	250	160
Clusters	2,860	140	2,400	100	190	80	260	90
Warm clusters	2,700	170	2,270	100	280	130	150	110
Cool clusters	3,050	220	2,540	180	100	70	370	130

Table 132. Regional annual hot water energy use by fuel (kWh/house with fuel)

The absence of solid fuel use in Auckland and gas use in Dunedin/Invercargill does not mean these fuels are not used for water heating in these locations – rather that HEEP did not monitor these uses. It is likely that there are relatively few such houses.

24.3 Providing domestic hot water

Historically the provision of domestic hot water (DHW) divides neatly into two categories:

- **batch production**, often based on carrying cold water to a pan or other holder above a fire; and
- **constant production**, with piped water flowing into a device heated by electricity, gas or solid fuel.

Figure 123 illustrates the different types of hot water cylinders in the HEEP sample, which were all of the continuous production type i.e. as water was drawn off replacement water flowed in to be heated. The few batch heaters e.g. laundry copper, were not in regular use.

Electric D-grade | Electric B-grade | Electric A-grade | Gas Instant | Gas Storage

Figure 123: Examples of hot water cylinders

Appendix 6: Historical Review of Hot Water provides an historical review of the provision of hot water in New Zealand homes.

24.3.1 Building Code requirements

Prior to the Building Act 1991 local authorities adopted their own by-laws, but there does not appear to have ever been any compulsion for dwellings or residential buildings to have hot water. However, if hot water was provided then there were certain requirements, and the 1965 Amendment, Clause 40 (2)(d), required in licensed premises that 'all baths, showers and lavatory basins shall at all times be provided with an adequate supply of hot and cold water laid on'.

The current New Zealand Building Code (NZBC) (regulations made under the Building Act 2004) largely continues this situation. NZBC Clause G12.3.5 requires that sanitary fixtures and sanitary must have hot water for utensil washing while in housing, retirement homes and early childhood centres hot water must also be available for personal washing; showering; or bathing.

Table 133 gives the Objective of Clause G12 as set out in Schedule 1 of the NZBC.

Objective

G12.1 The objective of this provision is to-

(a) safeguard people from illness caused by contaminated water:

(b) safeguard people from injury caused by hot water system explosion, or from contact with excessively hot water:

(c) safeguard people from loss of amenity arising from-

- (i) a lack of hot water for personal hygiene; or
- (ii) water for human consumption that is offensive in appearance, odour, or taste

(d) ensure that people with disabilities are able to carry out normal activities and functions within buildings.

Table 133: Building Regulations 1992 Clause G12 – Objective

Table 134 sets out the Performance Statements under Clause G12 that deal with hot water. Since 1992, Clause G12.3.5 (b) sets out a requirement for hot water to provided for personal washing, showering and bathing in housing, retirement homes and early childhood centres.

G12.3.5 Sanitary fixtures and sanitary appliances must be provided with hot water when intended to be used for–
(a) utensil washing; and
(b) personal washing, showering or bathing.
(Performance G12.3.5(b) shall apply only to housing, retirement homes and early childhood centres.)
G12.3.6 Where hot water is provided to sanitary fixtures and sanitary appliances, used for personal hygiene, it must be delivered at a temperature that avoids the likelihood of scalding.
…
G12.3.8 Vessels used for producing or storing hot water must be provided with safety devices that–
(a) relieve excessive pressure during both normal and abnormal conditions; and
(b) limit temperatures to avoid the likelihood of flash steam production in the event of rupture.
G12.3.9 A hot water system must be capable of being controlled to prevent the growth of legionella bacteria.

Table 134: Building Regulations 1992 Clause G12 – Performance (hot water)

The requirements of the Performance Statement are in turn met by the Acceptable Solutions and Verification Methods. Table 135 sets out the portion of the Acceptable Solution to Clause G12: Water Supplies which deals with ‘Temperature Control Devices’ and ‘Safe Water Temperatures’. In broad terms, the Acceptable Solution requires thermostats of a quality set out in the appropriate Standards, safety cut-outs to control dangerous temperatures, appropriate temperature limiting mechanisms (to a level depending on the type of users) and a storage temperature to limit possibility of infection from *Legionella pneumophila (*Legionnaires' disease) bacteria.

6.5	**Temperature control devices**
6.5.1	Electric thermostats shall comply with NZS 6214 or AS 1308.
6.5.2	Energy cut-off devices shall be designed to: a) Be reset manually, and b) Disconnect the energy supply before the water temperature exceeds 95°C.
6.14	**Safe water temperatures**
6.14.1	**Maximum temperatures** The delivered hot water temperature at any sanitary fixture used for personal hygiene shall not exceed: a) 45°C for early childhood centres, schools, old people’s homes, institutions for people with psychiatric or physical disabilities, hospitals, and b) 55°C for all other buildings. COMMENT: 1. At greatest risk from scalding are children, the elderly, and people with physical or intellectual disabilities, particularly those in institutional care. 2. Sanitary fixtures used for personal hygiene include showers, baths, hand basins and bidets.
6.14.2	**Hot water delivered from storage water heaters** a) An acceptable method of limiting hot water temperature delivered from storage water heaters is to install a mixing device between the outlet of the water heater and the sanitary fixture. b) Tempering valves shall comply with NZS 4617 or AS 1357.2.
6.14.3	**Legionella bacteria** Irrespective of whether a mixing device is installed, the storage water heater control thermostat shall be capable of being set at a temperature of not less than 60°C to prevent the growth of Legionella bacteria.
6.14.4	The water temperatures within flow and return circulating systems shall be maintained at not less than 60°C.

Table 135: NZBC G12/AS1 – Water Temperature & Control (3rd Edition 2006)

When hot water cylinders are replaced on a like-for-like basis, e.g. if a failed cylinder is replaced by a new one of the same size and pressure, then if no tempering valve was present a new one is not required.

24.4 International comparisons

It is easy to assume that the use of DHW and the systems used to provide hot water are internationally comparable. In order to explore this issue, data were obtained for an international comparison from the sources listed below:

- **Australia** – data for 2003 (ABS 2005)
- **Canada** – Energy Use Handbook 2005 (NRC 2005)
- **Europe** (selected countries) – various data sets from 1992 to 1995 (Lechner 1998)

- **England** – 2001 English House Condition Survey (ODPM 2003)
- **New Zealand** – 1996 Census (Statistics NZ 1998)
- **USA** – 2001 Residential Energy Consumption Survey (EIA 2004).

It should be noted that the different sources cover different time periods, and it is likely that different definitions have been used in the selection of statistics. As far as possible, appropriate adjustments have been made to ensure consistency based on the available documentation. For comparison with New Zealand data, it has been assumed that a house may have more than one method of heating hot water, e.g. electricity and solid fuel.

In particular, Lechner (1998) notes that their hot water system data for Germany and Portugal are of less certainty than for the other countries. The data for New Zealand are from the 1996 Census, the last time the question was asked.

24.4.1 Electric hot water

Figure 124 provides an international comparison of the percentage of houses using electric hot water storage systems. The data sources are listed above and at the top left of Figure 124. The percentages of houses with electric hot water storage systems range from 5% in Greece through to 88% in New Zealand (see Figure 188). The average for all Europe is 32%, while the two countries closest to New Zealand are Australia and Canada, both with 51%.

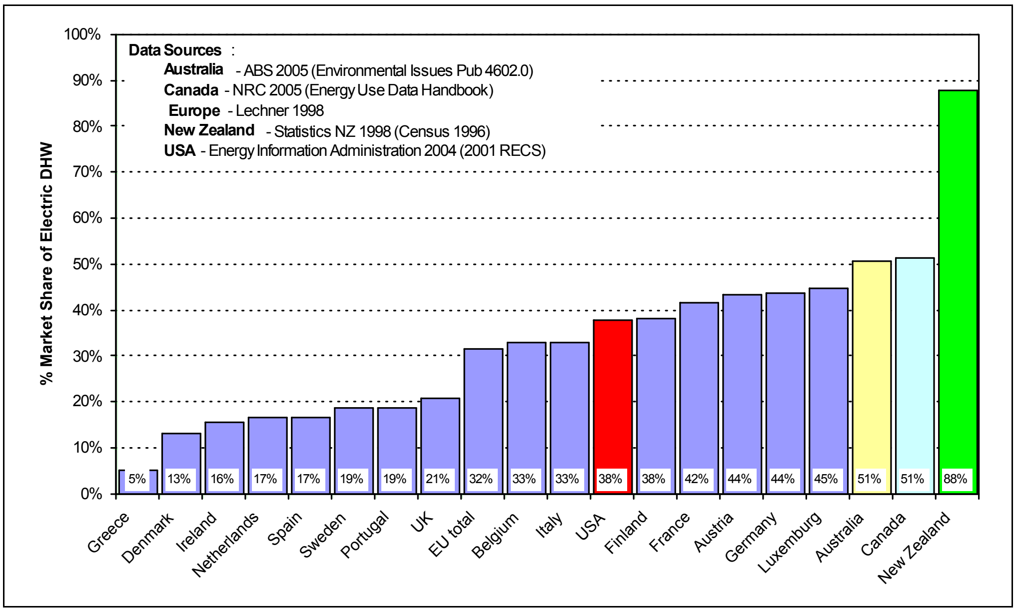

Figure 124: Residential use of storage electric hot water systems

Table 136 compares the proportions of households (or 'dwellings') with the different fuels used for water heating in the USA, England, Australia, New Zealand and Canada. Note that the total may be greater than 100%, as some homes have more than one hot water fuel.

DHW fuel	USA RECS 2001	England ODPM 2001	Australia ABS 2005	NZ Census 1996	Canada NRC 2003
Electric	38%	12%	51%	88%	51%
Natural gas	54%	76%	36%	8%	44%
Fuel oil	4%				4%
LPG	3%		3%		
Other (inc Don't Know, Solid)	1%	12%	12%	19%	0%

Table 136: DHW fuels – international comparison

New Zealand stands out as having the highest (88%) proportion of electric hot water systems while England has the highest proportion (76%) of natural gas systems. Australia and Canada have similar proportions of electric systems (51%), but there are more natural gas systems in Canada. The ‘Other’ fuels in Australia include solar water heating, bottle LPG and solid fuel systems.

An examination of countries for which regional data is available suggests a link between the use of hydro-electricity and the proportion of houses served by electric hot water systems.

A state-by-state examination of Australia reveals that Tasmania (90%) has the highest proportion of electric systems, followed by Queensland (68%) and New South Wales (64%) (ABS 2005). Ninety percent of Tasmanian electricity is generated from hydro sources (Hydro Tasmania 2005).

The large majority of Tasmanian hot water systems are mains pressure storage cylinders ranging in nominal size from 160 to 315 litres, depending on household size. There is an element size limit of 16 W/litre of cylinder capacity in order to reduce the hot water peak load, as most are on a continuous tariff i.e. a 180 litre tank can have a maximum 2.9 kW element (Pers. Com. Soheil Haee, Aurora Energy, 29 May 2006).

For Canada, the 2003 Survey of Household Energy Use (OEE 2006) shows that Québec (93%) had the highest percent of electric hot water systems followed by the Atlantic region (73%). Ninety-one percent of Quebec electricity is generated from hydro (82%) or nuclear (9%) sources, while the figure is 90% (87% hydro, 3% nuclear) in the Atlantic region (Statistics Canada 2004). Due to the extremely cold winter temperatures and the potential for pipes to freeze, Canadian domestic water heating systems are generally located in the basements of most houses. Typically these are mains pressure storage (pers. com. David Ryan, Director, Canadian Building Energy End-Use Data and Analysis Centre (CBEEDAC), 1 June 2006). The general tendency is for new Canadian houses to use natural gas rather than electricity for DHW (Aguilar et al 2005).

Figure 124 and Table 136 suggest New Zealand has a unique national situation, with a very high level of electric storage water heaters. However, even in countries with a relatively low overall proportion of electric storage hot water systems there are regions with even higher proportions that are found in New Zealand. In addition, New Zealand has a very high proportion of low pressure hot water systems.

24.4.2 Electric cylinder pressure and sizes

Mains pressure storage systems are the most common type of electric water heating in European households. However, there is considerable national variation (Lechner 1998):

- **German** households tend to have a number of smaller cylinders.
- **France** has an increasing use of ‘combis’ (combined hot water and space heating).
- **U.K.** mainly uses single-walled open-vented copper cylinders either indirectly heated by the central heating boiler (usually supplemented by an electric immersion heater) or used in conjunction with off-peak electricity. Until 1989 regulations forbade the storage of more than 15 litres of mains pressure hot water, but with the law change unvented and other hybrid versions are being used.
- **Italy** has been an electric water heater market, but is moving increasingly towards combis and cylinders heated indirectly by the central heating boiler.
- **Spain** uses mainly LPG water heaters but there is a significant use of electric water heaters. Natural gas combi boilers are gaining in popularity in new and existing dwellings.
- **Portugal** has a rapidly increasing number of households with hot water – in 1988 38% of households had no hot water but this fell to 14% in 1994. Instantaneous gas

water heaters are most commonly used, but domestic electric storage water heaters (DESWHs) are common in the north of Portugal, where cheap electricity was available until some years ago. The new natural gas network will encourage the change from electric water heaters to gas appliances.

- **Belgium and the Netherlands** both traditionally use instantaneous gas water heaters. In the Netherlands, combis have gained a large share but have proved less popular in Belgium. Dwellings connected to the gas network have tended to stay with dedicated gas water heaters, while those without gas have opted either for electric water heaters or for indirect heating (in Belgium, oil-fired rather than gas boilers).
- **Austria** has electric water heating as the norm, with gas confined mainly to Vienna.

The total number of installed DESWHs in the EU in 1992 was 45.2 million. Four countries – Germany (15.2 million = 33.6%), Italy (9.5 million = 21.1%), France (8.8 million = 19.5%) and the UK (4.8 million = 10.5%) – account for 85% of the total stock.

Figure 125 compares the electric hot water cylinder sales for New Zealand (EECA 2006, pers. com.) and estimated sales for selected European nations (France, UK, Germany, Ireland, Spain, Portugal, Belgium, Netherlands, Austria and Switzerland) based on Lechner (1998).

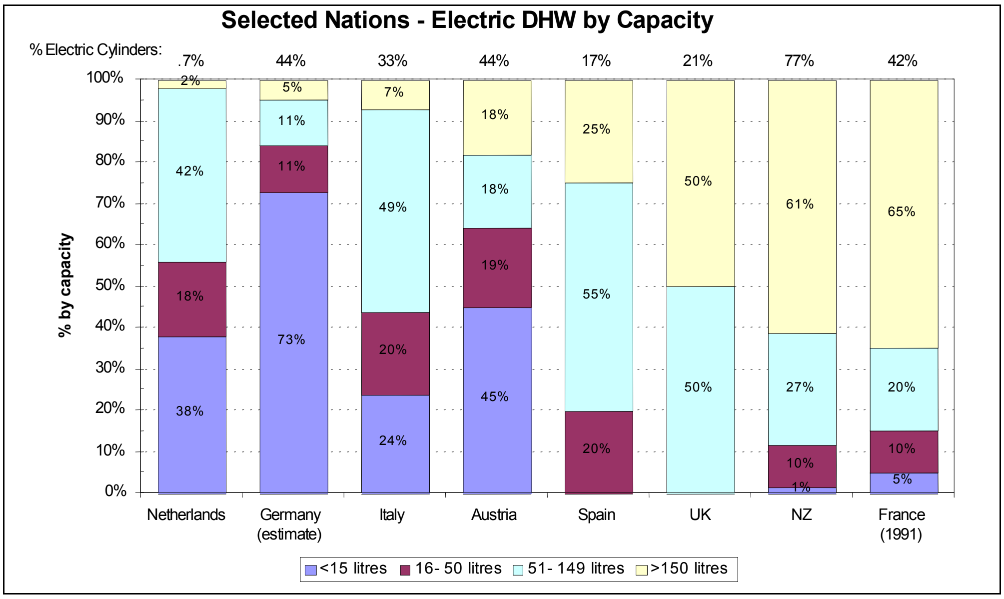

Figure 125: Selected nations - electric hot water cylinders by capacity

Figure 125 shows there is a wide variation between European countries in the distribution of the water storage capacity of the DESWH stock. For example, whereas 73% of Germany's DESWHs have a capacity below 15 litres (since households use several small units), in France 65% of DESWHs have a capacity greater than 150 litres partly as a result of promotional campaigns (Lechner 1998).

Country (Reference Year)	Storage capacity (litres)	Consumption (kWh/yr)
Austria (1990)	<15	1,000
	>15	2,200
France (1995)	Mean	2,400
Germany (1991)	<15	1000
	15–200	2,000
	>200	2,400
Portugal (1991)	Mean	3,100
New Zealand (HEEP)	Mean	2,400

Table 137: Average DHW energy use by capacity

Table 137 compares the average electricity use of domestic electric storage water heaters in Austria, France, Germany, Portugal and New Zealand (Lechner 1998). The spread of cylinder sizes makes a detailed comparison difficult, but comparing to the larger sizes New Zealand electric storage cylinders would appear to have similar electricity consumption to those in Austria, France and Germany, while those in Portugal would appear to consume more.

In the four European countries listed in Table 137, electric hot water accounts for 14% to 19% of household electricity consumption compared to 34% in New Zealand (Figure 6).

24.4.3 Shower flows

Appendix 6: Historical Review of Hot Water provides information and data from studies undertaken in North America, Australia and the UK on household shower water use and flow rates. No published survey has been carried out on water use by individual appliances (including showers) in New Zealand homes.

Internationally reported average shower flow rates are:

- 4 $L.min^{-1}$ (low-flow, North America)
- 7 $L.min^{-1}$ (non-low flow, North America)
- 9 $L.min^{-1}$ (Perth, Western Australia)
- 10 to 17 $L.min^{-1}$ (Sydney, New South Wales),

24.5 Hot water Energy Use

Figure 13 showed hot water uses on average 29% of household energy. Although domestic hot water is not the largest single household energy use, it is often the largest energy use in a single appliance. This proportion of household energy was consumed in one cylinder in 90% of the HEEP houses, two cylinders in 9% and in three cylinders in 1% of the HEEP houses. Domestic hot water uses 34% of household total electricity, 62% of gas, 7% of wetback and 73% of oil energy.

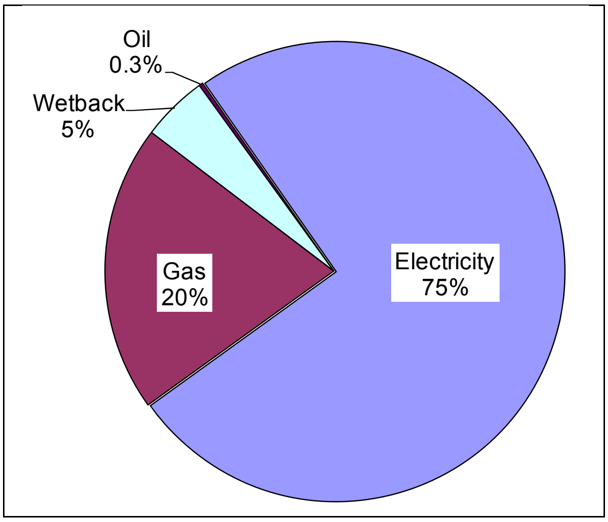

Figure 126: DHW Fuels

Figure 126 gives the average proportions of the different DHW fuels across all the HEEP houses. The variations in the proportions are illustrated in Figure 127 while the variations in the annual energy use are given in Figure 128.

These figures are based on the 311 houses for which full year data are available. The box indicates the first, second and third quartiles (bottom, mid-line and top of the box). The 'whiskers' are calculated to span:

$$1.5 * (Inter - quartile\ range)$$

Outliers are shown as unconnected horizontal lines. Note that the different statistics in Figure 127 and Figure 128 do not necessary reflect to the same houses, i.e. the minimum proportion house in Figure 127 may not be the same house with the minimum energy use in Figure 128,

Figure 127 shows that hot water energy use ranges from a minimum of 4% of total household energy use to a maximum of 74%. Half of the houses used between 22% and 40% of household energy for the provision of domestic hot water.

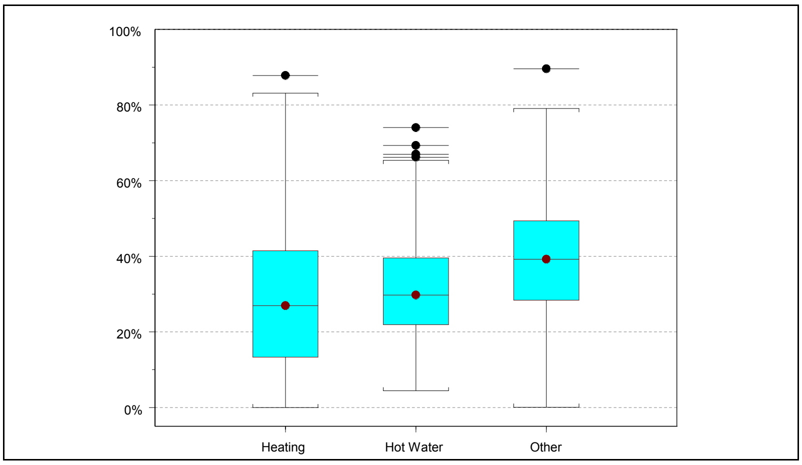

Figure 127: Variation in proportions of energy end-uses

The variation in annual use shown in Figure 128 ranges from a minimum of 750 kWh to a maximum of 13,900 kWh. Hot water energy use in half the houses ranges between 2,000 and 4,000 kWh/yr.

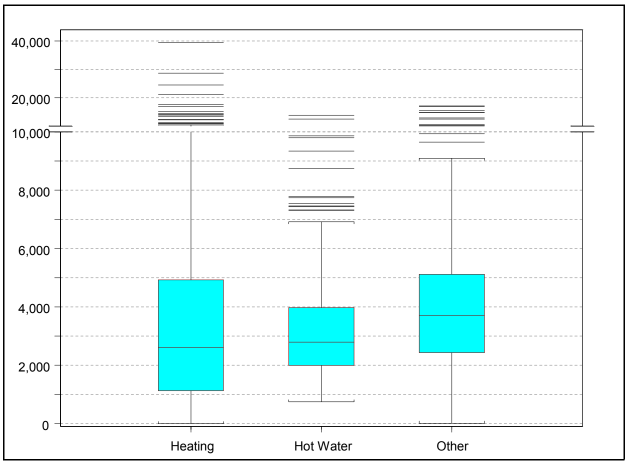

Figure 128: Variation in energy end-uses

Table 138 gives the range in kWh and the percentages for the main end uses (space heating, water heating and other) for each of the 311 houses for which full data is held.

End use	Heating	DHW	Other	Heating	DHW	Other
Minimum	-	750	10	0%	4%	0%
1st Quartile	1,130	1,990	2,440	13%	22%	29%
Median:	2,600	2,790	3,710	27%	30%	39%
Mean:	3,790	3,260	4,120	29%	31%	39%
Standard Deviation	250	110	140	1%	1%	1%
3rd Quartile	4,840	3,970	5,110	41%	40%	49%
Maximum	39,400	13,870	17,100	88%	74%	90%

Table 138: Energy & proportion of main end-uses

Since HEEP only monitored 400 houses, it is highly unlikely that either the highest or lowest hot water energy-using household in New Zealand was monitored. The national maximum will most likely be higher and the national minimum lower. However, statistical arguments suggest that with a 95% confidence, less than 0.75% of houses will fall outside the observed range of 750 kWh/yr to 13,900 kWh/yr.

24.6 DHW energy use distribution

Although central tendency statistics (mean, median and mode) are commonly used to help understand patterns, they do not provide guidance on the spread. A cumulative density plot provides an easy way to visualise data, and to examine the pattern of use. In particular, the percentage of households that have energy consumption that is greater or less than any given threshold can be easily seen.

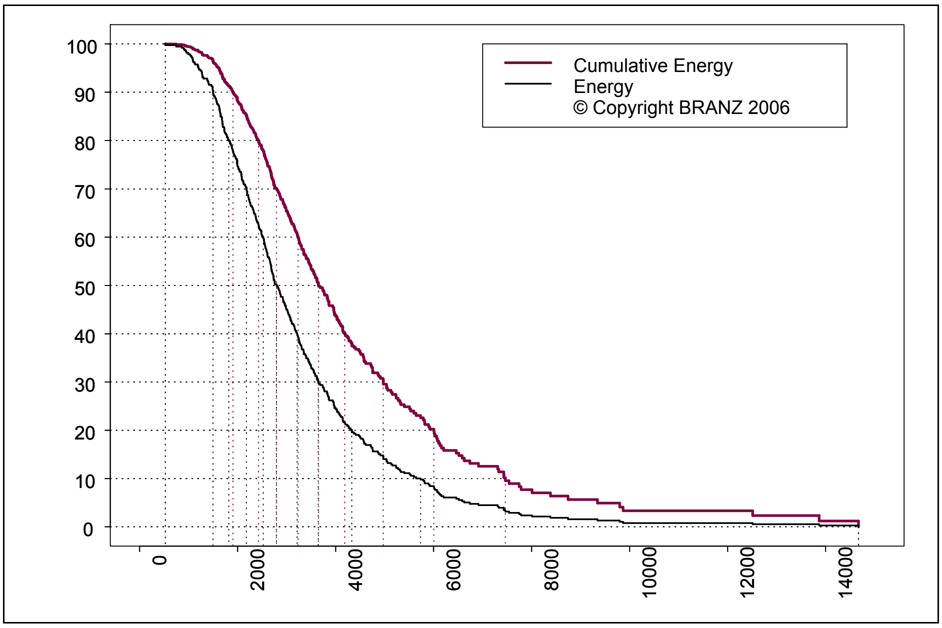

Figure 129: DHW Energy use distribution – all fuels

Figure 129 provides two cumulative density plots on common axes. The range of hot water energy consumption in kWh/yr is on the horizontal axis. The topmost curve (thicker red) shows the percentage of hot water energy consumption used by houses at or exceeding this level of energy consumption. The lower curve (thinner black) shows the percentage of houses at or exceeding this hot water energy consumption. In both cases the relevant percentage (of total hot water energy or households) is shown on the vertical axis.

Reference lines are drawn from the horizontal or vertical axis until they meet the relevant curve, and then traced to the other axis. For example:

- a horizontal line drawn from the 20% mark until it intersects the energy curve, then dropped vertically down to the X-axis intersects at 3,750 kWh/yr
- a vertical line up from 3,750 kWh/yr until it intersects with the cumulative energy curve, and then taken horizontally across to the Y-axis intersects at 37%.

Thus Figure 129 shows that the top 20% of households use more than 3,750 kWh/yr, and these households account for 38% of the energy used in all households. Conversely, the bottom 20% (80% on the Y-axis) of households use less than 1,820 kWh/yr, but they account for only 9% of the total household DHW energy use.

Table 139 uses Figure 129 to provide information on the highest and lowest 20% of hot water energy use for total fuels and separately for electricity, gas, LPG and solid fuel. The ratio of the energy use per house for the top 20% of houses to the bottom 20% of houses is about 2.2 for electricity and gas. For solid fuel wetback heaters the ratio is 6.9, showing a relatively small number of very high users account for the majority of water heated by wetbacks.

Figure 129 and Table 139 suggest that for a goal of reducing hot water energy use (i.e. energy conservation), the largest absolute reductions could come from the top 20% of houses. It also suggests that in shifting houses away from solid fuel burner wetbacks, a relatively small number of houses could make a disproportionately large impact on the energy supply system.

Fuel	**Bottom 20%**		**Top 20%**		**Ratio**
	Use under:	**% of energy**	**Use over:**	**% of energy**	**Top:Bottom**
Electricity	1,600 kWh/yr	9%	3,750 kWh/yr	37%	2.3
Gas	3,300 kWh/yr	13%	7,320 kWh/yr	27%	2.2
Wetback	180 kWh/yr	3%	1,240 kWh/yr	55%	6.9
All fuels	**1,820 kWh/yr**	**9%**	**4,330 kWh/yr**	**37%**	**2.4**

Table 139: DHW Fuel use – top and bottom 20% of houses

The following three figures provide energy and cumulative energy density curves for:

- Figure 130: electricity
- Figure 131: gas (mains natural gas and large cylinder LPG)
- Figure 132: wetback.

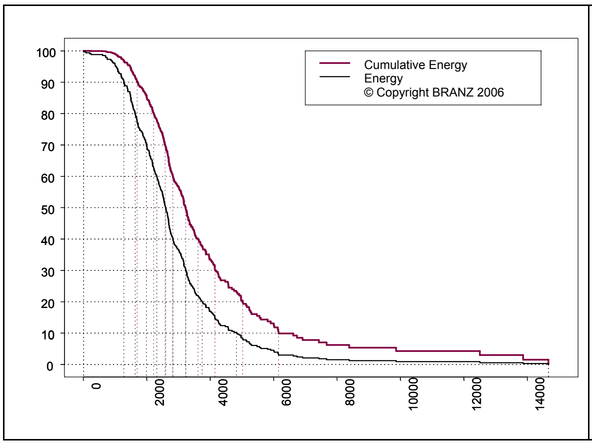

Figure 130: DHW electricity distribution

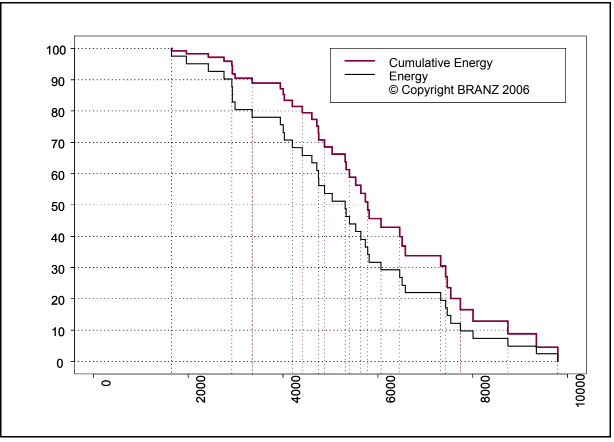

Figure 131: DHW gas distribution

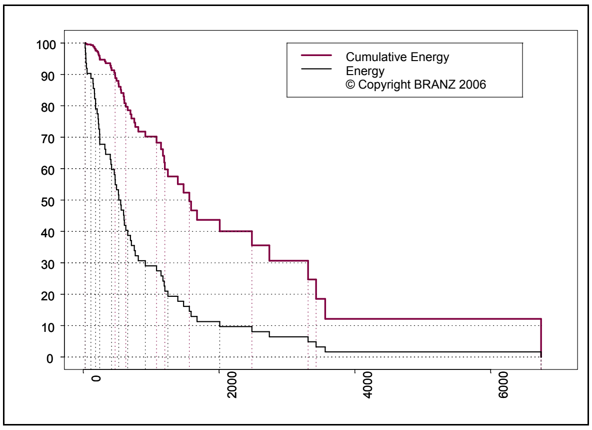

Figure 132: DHW Wetback distribution

Houses vary greatly in the time of use of hot water. This is illustrated by the profiles of 44 HEEP houses shown in Figure 133. The x-axis ranges from midnight to midnight in each graph. Each profile has been standardised (so that it has a mean of zero and a standard deviation of one), as the graphs are to be used to examine when hot water is being used. The clear conclusion is that there is no such thing as a 'typical' hot water usage pattern. As an illustration of the type of analysis that can be carried out on the data, Figure 134 shows monthly DHW profiles for a selected region. The HEEP data has the potential to permit categorisation of the use patterns by time-of-day, month or season.

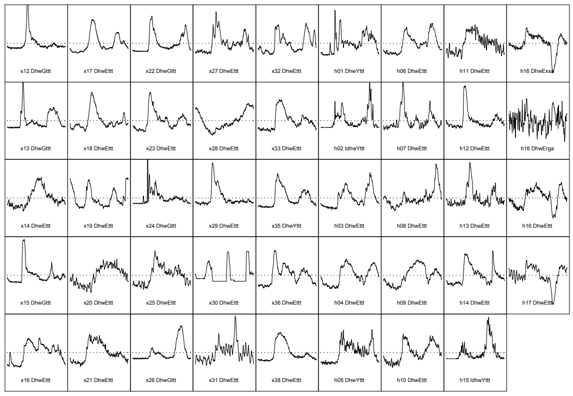

Figure 133: Average DHW energy profiles

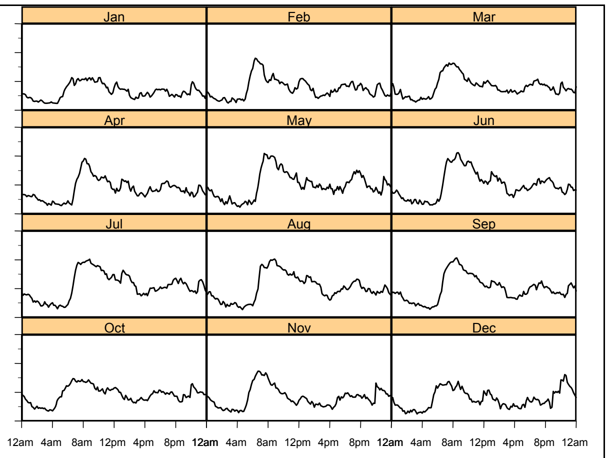

Figure 134: Monthly hot water energy profiles

24.6.1 Monthly DHW energy use

Is there a seasonal variation in hot water energy use? Figure 135 sets out for each of the three main fuel types (electricity, gas and solid fuel wetback) the monthly contribution to total national hot water energy use.

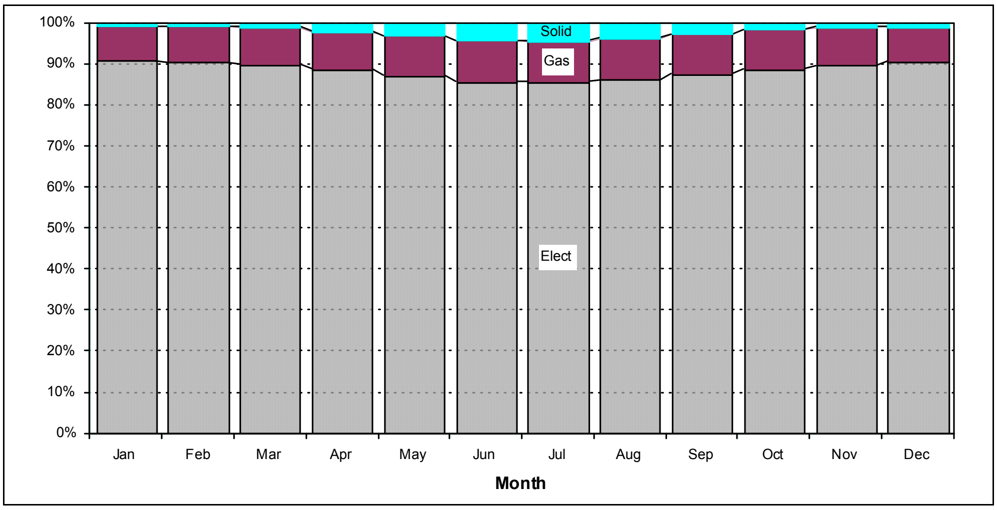

Figure 135: National Hot Water Energy Use by Month

Figure 135 shows that while the proportion of hot water provided by gas is largely constant over the year at around 9%, solid fuel is more important during the winter. In summer (January) solid fuel provides less than 1% of hot water heating energy while during winter (July) it provides 4.3%. It is the electric load that benefits from the solid fuel wetback – falling from 91% in summer to 86% in winter. Figure 136 and Figure 137 explore the variation by month for the different fuel types.

Figure 136 compares the energy use of wetback, gas and electric hot water systems as a proportion of the total annual average household energy use. It shows a very much stronger seasonal pattern of wetback use compared to the gas and electric systems. This is unsurprising as the wetback is driven by the household solid fuel heater, which is predominantly used in the cooler months.

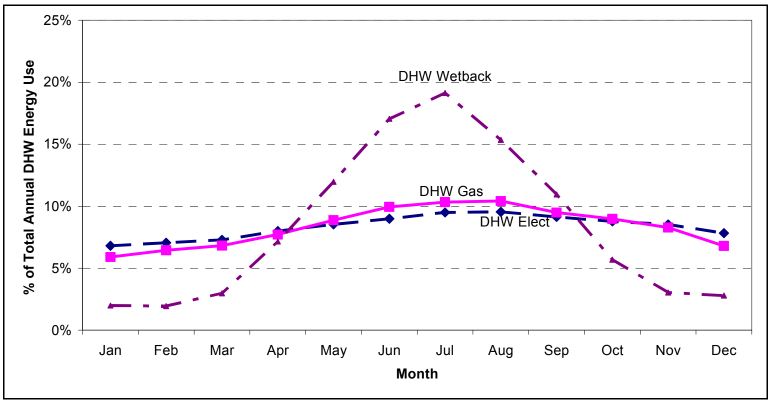

Figure 136: DHW Energy use by month

Figure 137 shows the average monthly energy use (kWh/month) for the houses that use that fuel for hot water. The percentage of houses with that fuel are given in brackets ( ).

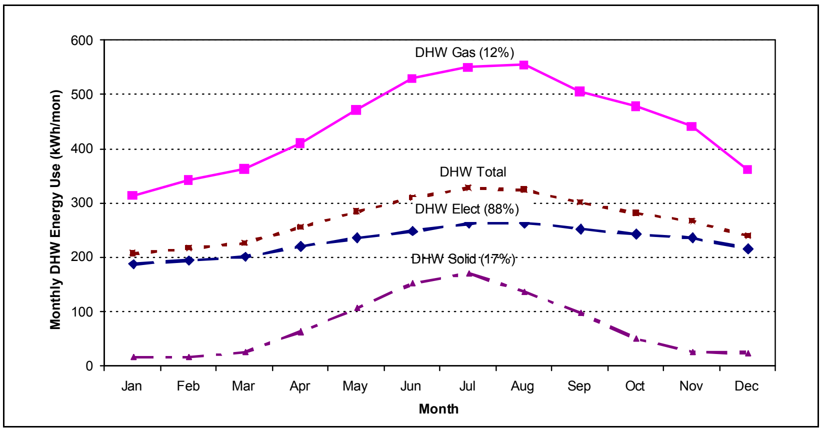

Figure 137: DHW Energy Use by Month for Houses with that fuel

24.6.1.1 Co-generation

Does this seasonal variation offer opportunities for the co-generation of electricity and heat?

Natural gas based co-generation produces larger amounts of heat than electricity. For example, the commercially available WhisperGen Stirling cycle engine generates 1 kW of electricity with a thermal heat output from 7.5-12kW[33].

Isaacs et al. (2007) examined household need for heat, and found that if all space and water heating was converted from electricity to a direct combustion fuel, e.g. natural gas, then during the coldest winter month (July), the average electric load was 0.5 kW (24 hours a day for each day of the month) while the heat load was 1.7 kW – a ratio of 1:3.3. During summer the ratio was only 1:1.5. This would suggest that there may be some opportunities for on-site co-generation in New Zealand homes during the winter period, but there would be a need to deal with large amounts of unused heat during the summer. The HEEP data would provide an ideal way to explore the opportunities for onsite (or distributed) natural gas based co-generation.

24.6.2 Changes in hot water energy use

Hot water is dominated by electricity, as shown in Figure 126. Three-quarters (75%) of 'purchased' energy for hot water is from electricity (i.e. the energy as delivered to the heater, not as delivered into the hot water after appliance efficiency is taken into account). In 2004, 14.1% of New Zealand households had a gas mains connection (Statistics NZ 2004h). Unfortunately, the Household Economic Survey has recorded only the presence of hot water systems since 1998 (Statistics NZ 1999h) and does not publish the fuel types.

Only a few energy end-use estimates had been prepared prior to HEEP:

- **Supply curves of conserved energy:** Wright and Baines (1986) provided the first comprehensive estimate of energy end-uses in the residential sector. They note that "data for estimating energy use in domestic water heating are not plentiful" and reference their data to the 1971/72 Household Electricity Study (NZ Dept of Statistics 1973), and electric supply authorities which meter water heating separately.
- **EECA End-use Database:**[34] The EECA database is a top-down estimation of more detailed information, allocating energy use to different sectors, regions, end-uses, technologies and fuels based on known information about the distribution of sectors and what energy they use and how they use it. First prepared in 1995 (Aulakh 2000),

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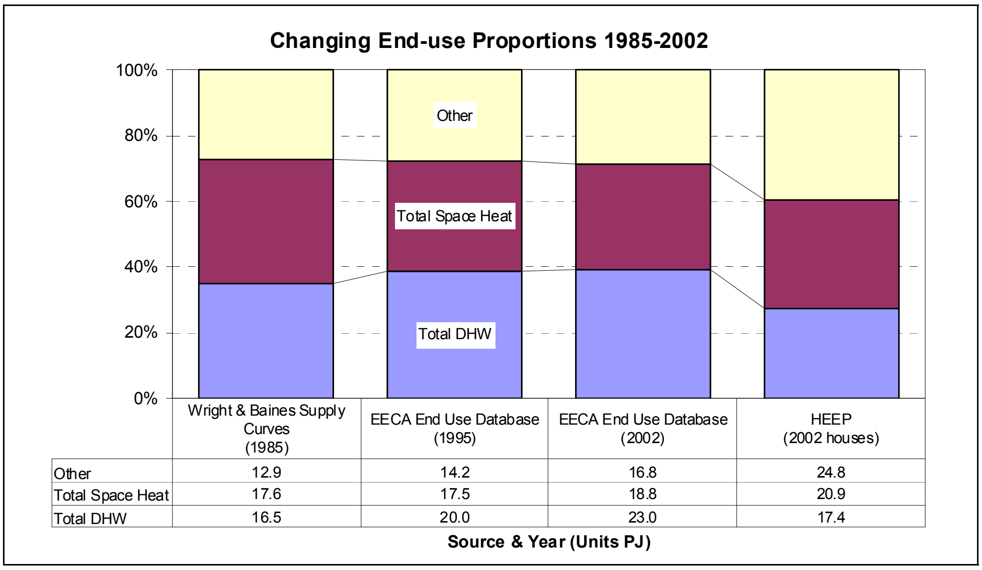
[33] See www.whispergen.com

[34] Available at: www.eeca.govt.nz/enduse/EEUDBMain.aspx.

it has been updated to 2002 and made freely available through the EECA website. It splits New Zealand energy use by 11 fuels, 32 sectors, 20 end-uses, 25 technologies and by all local authority geographical areas.

Figure 138 provides a comparison between the end-use data from Wright and Baines (1986), the EECA End-use Database for 1995 (Aulakh 2000[35]) and 2002 (web accessed), and the HEEP results.



	Wright & Baines Supply Curves (1985)	EECA End Use Database (1995)	EECA End Use Database (2002)	HEEP (2002 houses)
Other	12.9	14.2	16.8	24.8
Total Space Heat	17.6	17.5	18.8	20.9
Total DHW	16.5	20.0	23.0	17.4

Figure 138: Changing estimates of NZ residential energy end-uses

It can be seen from Figure 138 that the measurement-based HEEP work suggests a lower proportion of household energy is used by DHW than was previously thought – HEEP at 28% compared to 39% for the EECA End-use Database or 35% for Wright and Baines. It is not possible to determine whether this difference is due to changes over time or the different assumptions made in the earlier reports. It should be noted that the HEEP results do not necessarily suggest a decrease in hot water energy use, but rather a relative decrease due to increases in other energy uses.

24.6.3 Hot water energy use by household size

Although there are major differences between households, on average hot water use relates to the number of occupants. Per household consumption increases with the number of occupants up to 5 and then levels off (although there are very few households with more than 5 occupants).

Grouping	Average DHW Energy (kWh)	SE (kWh)	Percent of Households
1-3 occupants	2,590	80	56%
Over 3 occupants	4,370	230	43%
All households	3,130	100	100%

Table 140: Hot water energy use by number of occupants

Table 141 shows that on average, houses with over three occupants used 70% more hot water than households with under 3 occupants. About 90% of households with over 3 occupants used over 2,000 kWh per year compared to only 60% of 1-3 person households.

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[35] Table C8 *New Zealand energy end-use estimates by fuel type and by sector 1995.*

24.6.4 Standing losses

Standing loss estimates for hot water cylinders were reported in the HEEP Year 7 and 8 reports. The Year 10 report provided these final estimates, adding standing losses for wet-back hot water systems.

Table 141 lists for the four electric hot water cylinder standards the standard number and title. The letter grades (D through A) are used to represent the levels of cylinder standing losses. The 'worst' water cylinder lacked any insulation (i.e. bare copper), and would not even meet the D grade requirements. The nominal maximum standing losses for compliance with the standard are given for 135 litre (30 gallon) and 180 litre (40 gallon) cylinders.

Cylinder Grade	**Standard**	**Title**	**Standing Losses kWh/day**	
			135 l	**180 l**
A	NZS4305:1996	Energy Efficiency – Domestic Type Hot Water Systems	1.4	1.6
A	NZS 4602:1988	Low pressure copper thermal storage electric water heaters	1.4	1.6
B	NZS 4602:1976	Low pressure thermal storage electric water heaters with copper cylinders	2.8	3.2
C	NZS 720: 1975	Thermal storage electric water heaters with copper cylinders	2.8	3.2
D	NZS 720: 1949	Thermal storage electric water heaters	2.75	3.3

Table 141: Electric hot water cylinder standards

In the HEEP sample, 17% of the cylinders were A-grade; 37% B-grade; 8% C-grade; 33% D-grade and 5% could not be allocated a grade.

System standing losses were calculated in two ways. For those systems where a period of house vacancy could be identified (i.e. no water use), the standing losses during those periods were used. Where a vacancy period could not be found, the standing losses based on the energy use profile were used, provided that more than 10 recharge events per day on average occurred, which was a criterion established by comparison with the vacancy period estimates. Standing losses could be estimated for 262 of the hot water cylinders for which volume and grade data were also available. For wet-back hot water systems, where possible, standing losses were also estimated.

Table 142 provides estimates of cylinder standing losses by cylinder size and grade for 135, 180 and 270 litre electric storage cylinders and 135 and 180 litre gas storage cylinders. The 'grade' is based on the age of the cylinder and the appropriate standard (see Table 141). As there are only small numbers of A and C grade cylinders in the sample, and their theoretical standing losses are very close to those of B (for A grade) and D (for C grade) grade cylinders, Table 142 groups the grades into 'A or B', and 'C or D' grades, with a 'Wrapped' group for those with cylinder wraps. No grading data are available for the gas cylinders.

The calculated 'Standing Losses' are derived from the energy used to maintain the water temperature. The 'Cylinder Thermostat Temperature' represents the water temperature as delivered, while the 'Average Cylinder Temperature' takes into account the effect of the mixing of cold and hot water as the tank recharges. The difference between the average cylinder temperature and the 'Ambient Air Temperature' around the cylinder ranges from 37°C to 51°C, with an average of 43°C.

NZS 4602:1988 (Standards New Zealand 1988) assumes a temperature difference of 55.6°C between the stored water and the ambient temperature around the cylinder. Table 142 shows that this is not the case, with the temperature difference ranging from 40°C to 51°C, averaging 43°C for the 135 litre and 42°C for the 180 litre cylinders.

If the temperature difference is normalised to the Standard's 55.6°C then the standing losses would be approximately 30% higher, although it should be noted that the Standard measurement does not include the effect of attached pipes. Thus the savings attributable to installing cylinder wraps would be lower than calculated using the Standard standing losses.

Nominal Size & Grade	Total Energy (kWh/day) ±SD	Standing Loss (kWh/day) ±SD	No.	Cylinder Temp. (°C) ±SD	Avg. Cylinder Temp. (°C) ±SD	Ambient Air Temp (°C) ±SD
Electric - 135 litres						
A or B	6.5 ± 0.4	2.1 ± 0.1	51	64.3 ± 1.0	62.2 ± 1.1	18.4 ± 0.4
C or D	7.2 ± 0.4	2.8 ± 0.2	56	66.1 ± 1.0	63.9 ± 1.2	18.6 ± 0.4
Wrapped	6.4 ± 0.5	1.8 ± 0.1	9	63.7 ± 2.5	60.5 ± 2.8	17.8 ± 1.4
Other	12.6 ± 1.4	3.7 ± 0.3	19	60.1 ± 2.0	58.0 ± 1.9	18.8 ± 0.7
Electric - 180 litres						
A or B	7.8 ± 0.4	2.2 ± 0.1	76	62.8 ± 0.9	60.5 ± 0.8	18.6 ± 0.5
C or D	7.8 ± 0.6	2.7 ± 0.2	28	64.3 ± 1.5	61.0 ± 1.1	16.8 ± 0.6
Wrapped	7.6 ± 1.1	2.1 ± 0.3	10	59.4 ± 3.1	59.3 ± 4.1	17.7 ± 1.3
Other	14.2 ± 1.7	3.7 ± 0.3	14	59.6 ± 3.6	57.4 ± 4.3	16.6 ± 1.1
Electric - 270 litres						
A or B	8.1 ± 1.3	3.0 ± 0.4	8	62.3 ± 2.5	64.0 ± 2.2	19.7 ± 1.0
C or D	6.1 ± 1.8	2.6 ± 0.2	2	69.9 ± 8.6	69.5 ± 8.3	18.8 ± 0.8
Gas cylinders						
135 litres	14.1 ± 1.5	4.1 ± 0.3	15	60.4 ± 1.8	58.2 ± 1.8	19.1 ± 0.8
180 litres	17.3 ± 2.0	4.2 ± 0.4	9	56.3 ± 3.2	55.0 ± 3.8	17.7 ± 1.6

Table 142: Electric storage cylinder standing losses by size and grade

Table 142 shows that 'A or B' grade cylinders have lower standing losses than the 'C or D' group. This is statistically significant for both the 135 and 180 litre cylinders.

There are only a small number of 'wrapped' cylinders in the HEEP sample. However, the nine 135 litre wrapped cylinders have an average standing loss of 1.8 kWh per day, lower even than the 'A or B' grade cylinders. The wrapped 180 litre cylinders have an average standing loss of 2.1 kWh/day. Cylinder wraps clearly **do** work.

Standing losses for electric systems are about 33% of the total energy use, on average. Total energy use for gas systems is about double that of electric systems.

It should be noted that unlike the standing loss analysis presented in the HEEP Year 6 report (Isaacs et al, 2002 – Section 5.3.2), no adjustment has been made here to match the standing losses derived from the measured performance to the same conditions as set out in NZS 4602:1988 (Standards New Zealand, 1988).

Table 143 and Figure 139 provide estimates for total energy consumption and standing losses for four cylinder types: electric storage, electric night rate storage, natural gas storage and natural gas instant. Total energy use could be calculated for 405 hot water appliances, but data for standing losses was only available from 322 appliances.

Fuel & Appliance type	Total Energy (kWh/day) ±SD	Total Energy No.	Standing Loss (kWh/day) ±SD	Standing Loss No.	Loss % of Total Energy
Electricity Storage	7.4 ± 0.2	346	2.5 ± 0.1	279	33%
Electricity Night Rate	6.2 ± 0.6	16	2.6 ± 0.3	11	42%
Natural Gas Storage	15.6 ± 1.1	27	4.2 ± 0.2	26	27%
Natural Gas Instant	12.2 ± 1.5	16	0.0 ± 0.0	6	0%

Table 143: Total energy consumption and standing losses by HEEP system type

Total energy use ranges from 6.2 (electric night rate storage) to 15.6 kWh/day (natural gas storage). Note this data should **not** be taken to suggest that the fuel type or cylinder type are the only reasons for different energy use. This is further explored in Section 24.6.5.

Average standing losses as a percent of total energy use range from 27% (natural gas storage) to 42% (electric night rate storage). Section 24.13 explores the costs and benefits of improving cylinder thermal performance.

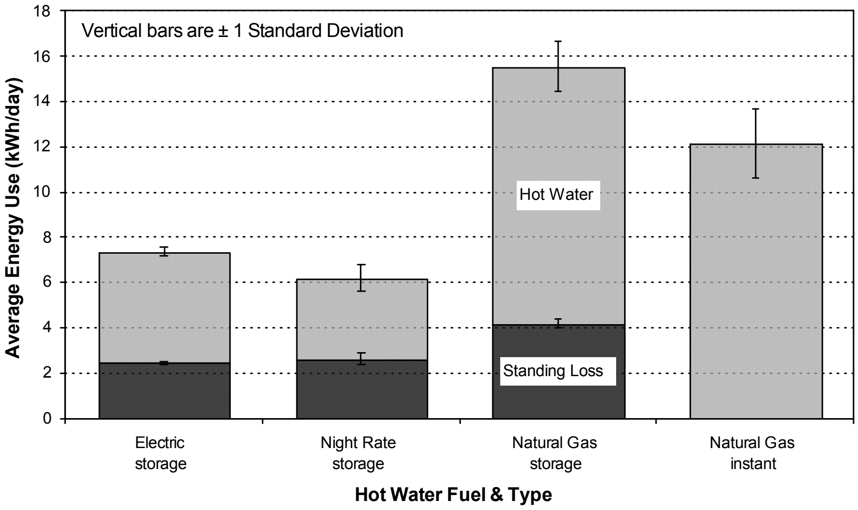


Figure 139: Energy consumption and standing losses by system type

24.6.5 Gas vs. electric hot water energy use

Figure 139 has been taken to suggest that houses with gas DHW systems use significantly more water and hence energy than electric DHW systems (e.g. CRA 2004). But why should this be the case – is there a link between the use of gas and the use of more hot water?

It must be recognised that Figure 139 gives average standing losses and energy use for by fuel for each of the cylinder types found in the HEEP houses. It does not report on the losses or hot water energy used for a specific house or DHW system

Table 144 provides a comparison of gas and non-gas fuelled DHW systems. In terms of total hot water energy use, non-gas systems use 56% of the energy used by gas systems. When the standing losses are removed, the ratio reduces slightly to 55%. However, 100% of the electricity provided to an electric cylinder is converted to hot water but the efficiency of a gas cylinder will be below this. Table 144 shows that assuming gas is converted to hot water at an efficiency of 80%, non-gas systems use 69% of the energy used by gas systems.

Fuel & Appliance type (±SD)	Total DHW inc standing losses	Hot water (Total - standing loss)	Delivered energy (gas 80% efficiency)	Count
Non-gas	2,886 ± 95	2,150 ± 127	2,150 ± 127	211
Gas	5,119 ± 338	3,914 ± 330	3,131 ± 264	41
Ratio Non-gas : Gas	56%	55%	69%	

Table 144: Household hot water energy use by system type

These comparisons have been made assuming that houses with gas and non-gas hot water systems have similar characteristics. However, Table 145 compares selected averages indicators showing that in almost all cases, houses with gas hot water are larger than houses with non-gas water heating. On average, houses with gas hot water have more occupants, more showers, use more shower water, and have higher equivalised income. They have nominally lower 'Total Volume' of hot water cylinders, possibly due to the faster response time of gas water heaters. In part, the lower cylinder volume is due to the larger number of 'instant' gas water heaters (which are recorded as having zero volume) but there are also a reasonable number of smaller electric cylinders (see Table 154).

Variable for household	Gas (±SD)	Non-Gas (±SD)
Number of Occupants (average)	3.3 ± 0.2	2.8 ± 0.1
Floor Area (m²)	134 ± 7	119 ± 2
Shower Water Use Per Year ('000 litre)	136 ± 23	84 ± 5
Number of times shower used per week	19.8 ± 1.8	16.7 ± 0.6
Equivalised income	\$39,600 ± \$2,300	\$30,200 ± \$1,000
Total Volume of water cylinders	159 ± 8	170 ± 3

Table 145: Comparison gas & non-gas water heater households

The Luxemburg method (Atkinson et al 1995) has been used to calculate equivalised household income to control for household size effects. The equivalised income is calculated by dividing total household before tax income by the square root of the number of occupants. Total income is usually not as useful, as it does not relate well to disposable or discretionary income. A household with a total income of \$50,000 could have one occupant or six, probably with a very different standard of living. Table 62 gives quintile boundaries for the HEEP households.

Thus in order to compare the energy use in gas and non-gas systems, it is necessary to identify and remove the effects of income and other possible drivers of hot water use. Exploration of the data generated a linear regression model which is given in Equation 23 and the coefficients are summarised in Table 146, along with a brief description of each model term. There is no 'Equivalised Income' term in this model as it was not statistically significant. For the model the efficiency of gas conversion was included by assuming an efficiency of 80% for gas and 100% for non-gas.

Model Term	Description	Value	
(Intercept)		-1,235	
No Occupants	Average number of occupants per house	522	A
Main Means Gas	1 if gas is used, 0 if non-gas system	414	B
Floor Area	Total floor area excluding garages (m²)	8.04	C
Life Stage pre-school	Fraction of households whose youngest is pre-school age (0-5 yr)	0	D
Life Stage school age	Fraction of households whose youngest is school age (5-14 yr)	1,069	D
Life Stage working age	Fraction of households whose youngest is working age (15-64 yr)	799	D
Life Stage retired	Fraction of households whose youngest is of retirement age (≥65 yr)	358	D
Shower Water Use/Year	Volume of water used in main shower per year (Litres)	0.0026	E

Table 146: Regression model for hot water energy use

The model given in Equation 23, where A through E are the values given in Table 146:

$$\begin{aligned} HotWaterEnergyUse &= Intercept \\ &\quad + A * NoOccupants + B * MainMeansGas + C * FloorArea \\ &\quad + D * Lifestage + E * ShowerWaterUsePerYear \end{aligned}$$

Equation 23: Regression model for hot water energy use

The model is based on regional average data so the averages (nationally or per region) are used e.g. average floor area. For categorical variables such as **LifeStage** the fraction of households in each region that belong to each category is used as the variable. The model described in Table 146 has a multiple r^2 of 41.5%.

Life stage analysis can be a useful tool for exploring assumptions about individuals or households by categorising them into groups based on criteria such as age or accomplishment of some life event, for instance graduating school or purchasing a first home. For the HEEP households there were some assumptions about the different behaviours of retired households compared to, say, households with young children. All HEEP households were divided into one of four life stages based on the age of the youngest person in the house (see Isaacs et al. 2005). Table 147 lists the proportions of each life stage in the houses with gas and non-gas water heaters. It can be seen that houses with gas water heating have higher proportions of ‘school age’ life stage and lower proportions of ‘retired’ life stage households.

Life stage	Gas	Non-Gas
Life Stage ‘pre-school’	16%	15%
Life Stage ‘school age’	29%	21%
Life Stage ‘working age’	47%	47%
Life Stage ‘retired’	8%	17%

Table 147: Life stage by water heating fuel

Equivalised income is strongly related to life stage, with the overall pattern being higher equivalised incomes in households at the ‘working age’ life stage, while very few ‘retired’ life stage households are above Quintile 3. Quintile 5 households often have few people e.g. a single professional or a working couple.

The HEEP Year 5 report (Stoecklein et al. 2001) provided an analysis based on the then available water heating systems in 53 HEEP houses (predominately electric cylinders) leading to a linear model with variables: number of female teenagers, type of appliance (electric storage, natural gas storage, natural gas instant) and number of showers per week. Data from the full set of HEEP houses now generates the model provided in Equation 23 and Table 146. The life stage is still important, although female teenagers no longer hold their own variable.

Table 148 uses Equation 23 with the values from Table 146, the life stage proportions from Table 147 and the values in Table 145 as appropriate for households with non-gas or gas water heaters. For example, the gas water heater household has 3.3 occupants while the non-gas water heater household has 2.8 occupants. The calculated energy uses for the gas and non-gas households are within 3% of the values from the HEEP work (from Table 144 *given in italics*).

The rightmost columns of Table 148 provide the difference between the non-gas and gas hot water households and calculate the proportion of the total difference due to each variable. The number of occupants accounts for 24% of the difference, the amount of shower water 14% and the house floor area 13%. Each of these has a reasonably direct physical link e.g. even if each person uses the same amount of water, the more people the greater the total shower water use. There is a strong correlation between floor area and the number of people, so this may be driving the inclusion of the floor area term. This analysis takes into account the lower efficiency of direct burning gas hot water cylinders and the differences between houses with gas and non-gas hot water systems. The last line in the table extracted from Table 144 shows how closely the equations match the actual non-gas and gas DHW energy use.

	Non-Gas		Gas			% of
Variable	Factor	Component	Factor	Component	Diff.	Diff
(Intercept)	1	-1,235	1	-1,235		
Number of Occupants	2.85	1,486	3.29	1,715	230	24%
Main Means = Gas	-	-	1	414	414	44%
Floor Area	119.48	961	134.41	1,081	120	13%
LifeStage 'school age'	0.21	224	0.29	310	86	9%
LifeStage 'working age'	0.47	375	0.47	375	0	0%
LifeStage 'retired'	0.17	61	0.08	29	-31	-3%
Shower Water Use/Year	84,190	219	135,727	353	134	14%
TOTAL NET ENERGY		2,092		3,044	952	100%
from Table 144 NET ENERGY		*2,150*		*3,131*	*981*	

Table 148: Linear model application – non-gas and gas water heating

The equations used to develop Table 148 show a difference of 952 kWh/year between electric and gas DHW systems. Of this 952 kWh/yr, only 414 kWh/yr can be attributed the use of gas i.e. 44% of the difference. 414 kWh/yr is 20% of the non-gas base use of 2,092 kWh/yr. The remainder of the difference (538 kWh/yr) is accounted for by the number of occupants, house floor area, life stage and shower use.

Thus in summary, the average increase in net energy use for houses with gas hot water that can be attributed to the use of gas is 20%. The reasons for this difference are unclear as there is no obvious physical cause, suggesting that there are drivers for use of gas water heating that are not simply physical. These could include the:

- ability of a gas hot water system to supply greater amounts of hot water (e.g. gas systems tend to meet higher hot water demands than electric systems);
- household requirements (e.g. those currently using gas self-select after becoming disenchanted with the service offered by the electric system).

Of the other differences, the use of flow control on mains pressure systems (e.g. low flow showerheads) is likely to have a noticeable impact.

This analysis reports the current situation, and is far from the suggestion apparently derived from earlier versions of Figure 139 and the HEEP Year 6 report (Isaacs et al. 2002) that houses with gas hot water use 3.6 times more water than houses with non-gas hot water (CRA 2004).

24.7 System types

All houses in the sample have one or more hot water systems, although not all systems are fully operational. Table 149 lists the HEEP codes for the various types of hot water systems, and the number of houses reporting each type in the survey. The number of systems is greater than the number of houses, as some houses have more than one type of hot water system.

Hot Water System (survey response)	System Count
Electric Storage Cylinder (incl. night rate)	314
Electric Storage + Solar Cylinder	3
Electric Storage + Solid Fuel	63
Electric + Solar + Solid Fuel	3
Solid Fuel only	2
Gas Storage	34
Instant Gas	20
Other	2

Table 149: **HEEP hot water systems**

Table 149 shows that the majority of the HEEP hot water systems (71% for the analysed sample) have only an electric storage water cylinder – an electric element located inside an insulated tank of water, with the temperature controlled by a thermostat. Sixteen percent of the systems have an electric cylinder with some form of supplementary heating, either solar, wet-back or a combination. Eight percent of the water heating systems are gas storage systems, 5% are instantaneous gas and less than 1% are solid-fuel-only. The small number of solar water heater systems (7 in total) has meant it is not possible to report them separately.

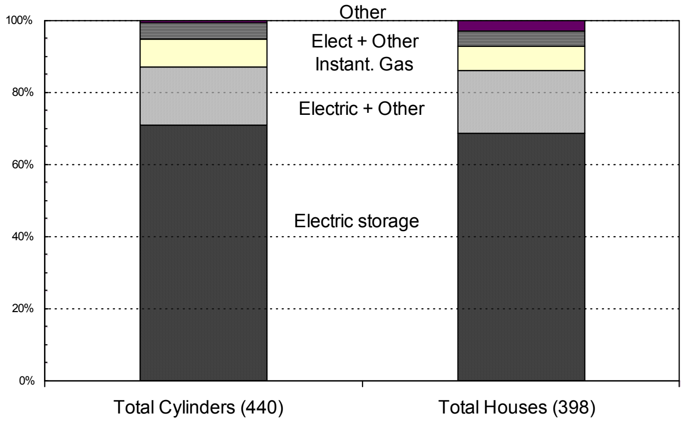


Figure 140: Hot water systems – by type and houses

Figure 140 gives the proportions of the different types of hot water systems for both the total number and the systems found in each house. The proportions are similar – the main difference relates to the houses with both electric and gas storage systems.

14% of the HEEP houses did not use electricity for water heating while in the 1971/72 study 12% of the houses did not have electric water heating.

24.7.1 Hot water service

People do not like to run out of hot water. As part of the HEEP survey, house occupants were asked: “Do you sometimes run out of hot water?” Eighteen percent of the households replied “Yes” to this question. (Question number B.2.18)

Table 150 summarises the responses categorised by the ‘main’ means of hot water heating. Note that where a house has had to be replaced in the sample (most often due to the occupants moving and the new occupants not wishing to continue as part of HEEP) the replacement is also included in this table. It should also be noted that each house may have more than one method of heating hot water, using one or more different fuel types. Numbers may not add to 100% due to rounding.

Do you run out of hot water?	Yes	No	No Answer
Electric storage	19%	76%	4%
Electric + Other	19%	79%	3%
Gas storage	18%	82%	0%
Gas instantaneous	0%	95%	5%
Other	0%	100%	0%
Overall average	**18%**	**78%**	**4%**

Table 150: Hot water adequacy by fuel type for randomly selected houses

Table 150 shows that on average 18% of households with natural gas or electric storage water heaters report that they ‘sometimes’ run out of hot water, with almost the same proportions for each. There was no shortage of hot water for other system types.

Examination by cylinder size also found no significant difference in the adequacy of hot water provision for houses with 135 or 180 litre cylinders, whether fuelled by natural gas or electricity.

Do you run out of hot water?	Mains Pressure	Low Pressure	Total
Electric Cylinder	15%	21%	20%
Gas Cylinder	18%	18%	18%
Instant Gas	0%	NA	0%
Electric + Solid fuel Wet-back Cylinder	0%	20%	20%
Average	**12%**	**21%**	**19%**

Table 151: Hot water adequacy by system pressure

Table 151 provides a breakdown by water pressure and fuel type for those households that answered this question (i.e. excluding ‘Don’t Know’). There does not appear to be a significant difference between the different fuel types and pressures for storage hot water systems. Instant gas systems, all of which are mains pressure, reported no problems with running out of hot water.

Only 9% of households have the hot water cylinder located outside the conditioned house space. Over three-quarters of households (80%) have the hot water cylinder located in a cupboard inside the house. For these, all waste heat (i.e. cylinder standing losses) will be contributing to the house winter space heating – in some cases, a significant proportion.

Two-thirds (66%) of households used the space around the hot water cylinder for linen or clothes storage.

Only 30 households reported the use of a hot water cylinder wrap.

24.8 Estimates of wet-back energy heat inputs

Solid fuel is used in many parts of New Zealand as a supplementary water heating fuel – Table 149 reveals that 15% of households have a ‘wet-back’ solid fuel water heater. APPENDIX 11: DHW Wet-back (Supplementary) Water Heating provides background to the analysis method used in HEEP to evaluate the water heating energy provided by solid fuel wet-backs (Isaacs et al. 2005).

The average wet-back provides 1000 kWh ± 200 kWh per year, or about 20% of the total hot water energy. About 5% of the houses with wet-back systems get all (i.e. 100%) of their hot water from the wet-back, although most of these are dedicated solid fuel water heaters rather than space heating units. Overall, roughly 5% of the national total hot water energy is supplied by wet-back water heaters (Figure 126).

There are still some chip heaters in use in New Zealand homes (seven chip heaters were used in the HEEP houses), even though many of them are very old (see Figure 192). There are a few modern chip heaters (like the ‘Butler’), though they are outnumbered by the older types and by wet-back connections to solid fuel burners.

Table 152 provides information by region on the percent of houses with wetbacks, and the average net energy and percent of total hot water the wetback contributes in houses that have them.

Area	% with wetback	SE	Average Net Energy (kWh)	SE	% DHW Energy	SE
Auckland	2%	1%	140	80	4%	3%
Hamilton	24%	11%	770	220	33%	14%
Wellington	5%	3%	250	220	7%	6%
Christchurch	22%	7%	441	140	12%	5%
Dunedin/Invercargill	20%	9%	1220	510	39%	16%
Warm Clusters	15%	4%	900	280	24%	5%
Cool Clusters	32%	5%	1100	270	27%	5%

Table 152: Wetback use by region

There is huge regional variation in both the presence and the energy provided by wet-back water heaters. Houses in the cool clusters (mainly in rural areas) have the highest proportion of wetbacks, although in Hamilton and Dunedin/Invercargill houses with wetbacks have over one third of their water heating provided by them. Some wetbacks provide only a few percent of the total hot water for a household, while some systems provide more than two-thirds. This is readily explained as in colder climates the solid fuel burners are used more often, more intensively, and for more months of the year, so more energy is fed into the wet-back circuit. This is also reflected in the number of wet-back systems, with few in warm climates, and a lot in cold climates.

In three of the 29 locations monitored, around 20% of all hot water energy was supplied by wet-backs, and in winter time this was nearly 50%, and even higher during the evening peak. In areas like this which often have a limited electricity supply capacity, it appears that wet-backs are making a large contribution to managing peak electricity demand in winter.

Wet-back systems generally have higher standing losses than electric cylinders alone, due to more pipes and pipe penetrations. The extra losses could be of the order of 0.4 kWh per day. About 90% of wet-back systems provided more energy than the extra standing losses over a year. For houses that do not use their wet-back, removing the pipes and sealing the holes with insulation would reduce standing losses slightly. The high losses coupled with the short operating hours suggest that wet-backs are not a good option for water heating in warm climates.

24.9 Storage cylinders

This section provides data on the different sizes, water pressure and age of hot water storage cylinders.

24.9.1 Cylinder sizes

There is a wide range of different hot water cylinder sizes in New Zealand homes – HEEP found 32 different sized electric cylinders and 9 different gas storage cylinders, not counting instantaneous systems which are assumed to have zero stored volume. For the purposes of analysis it has been necessary to group the different cylinder sizes. Figure 141 shows the size distribution – it is clear that the 135 litre and 180 litre cylinders are the most popular, although 24% of the electric only storage cylinders and 66% of the gas only storage cylinders are neither of these volumes. Table 153 tabulates the size ranges used to allocate other volumes to nominal sizes for the analysis reported here.

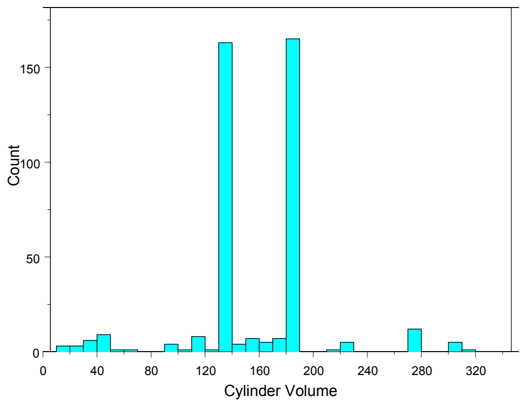


Figure 141: Cylinder volumes

Nominal Size	Volume Range
0	Instantaneous
25	0 ≤ 33.5
50	33.5 ≤ 55
75	55 ≤ 100
135	100 ≤ 150
180	150 ≤ 210
250	210 ≤ 275
350	275 ≤ 1000

Table 153: Cylinder volume range

Table 154 tabulates the number of hot water systems and the cylinder volume. As instantaneous gas water heaters do not store water, the cylinder size is reported as 'missing'. The majority of hot water systems are electric (384 out of 441 = 87%), so sizing distribution is dominated by electric systems.

Table 154 shows that most cylinders are either 135 litres (30 gallons) (42%) or 180 litres (40 gallons) (40%), with the remainder being split almost equally between the small cylinders located close to their end-use (e.g. under sink kitchen hot water) and larger cylinders. Six percent of the cylinders lack a 'volume' – in the main these are instantaneous systems, but in a few cases it was not possible to inspect the cylinder to determine the volume (e.g. the cylinder was completely built into a cupboard).

There are almost equal numbers of 135 litre (164) and 180 litre (165) electric cylinders – each 43% of the total number of electric storage cylinders. The distribution pattern differs for the smaller number of gas storage cylinders with 35% at 135 litres and 24% at 180 litres, but 33% are instantaneous (i.e. no water storage).

		Cylinder Nominal Volume							
System	**Missing**	**25**	**50**	**75**	**135**	**180**	**250**	**350**	**Total**
Electric Storage Cylinder (only)	7	10	10	5	133	142	4	3	314
+ Solar + Solid Fuel Wet-back	-	-	-	-	-	-	2	1	3
+ Solar Water Heater	1	-	-	-	-	1	1	1	3
+ Solid Fuel Wet-back	1	1	-	-	31	22	8	-	63
+ Oil	-	-	-	-	-	-	1	-	1
Gas Storage Cylinder (only)	2	-	-	1	18	12	-	1	34
Instant Gas Heater (only)	18	1	-	-	-	1	-	-	20
Instant Gas + Solar	-	-	-	-	1	-	-	-	1
Solid Fuel Storage Cylinder (only)	-	-	-	-	-	1	1	-	2
TOTAL	**29**	**12**	**10**	**6**	**183**	**178**	**17**	**6**	**441**

Table 154: Hot water systems by fuel source and cylinder volume

Cylinder size (volume) distribution varies by location. Close to half of the cylinders (49%) in the sample are in the top of the North Island, under one-third (31%) in the bottom of the North Island and the remaining one fifth (20%) in the South Island.

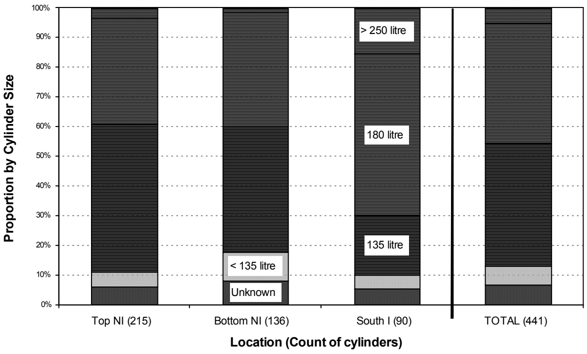


Figure 142: Cylinder size by region

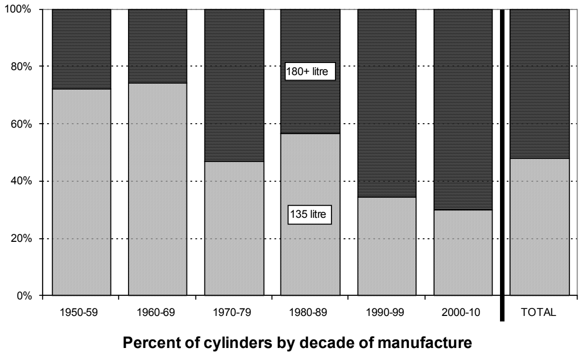


Figure 143: Cylinder size by age

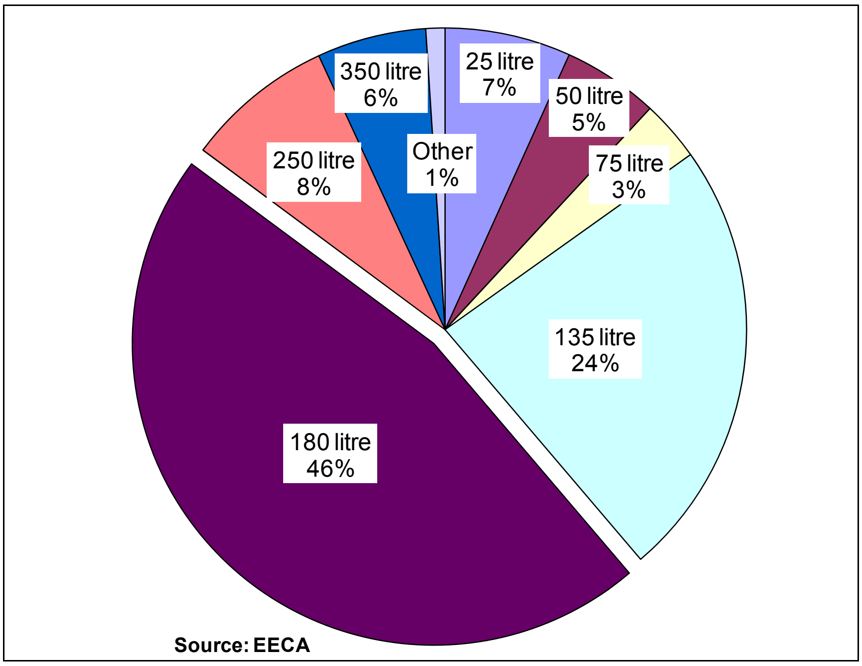
Figure 142 shows that in the upper North Island sample (Northland, Auckland, Hamilton, Tauranga etc.) 53% of the cylinders are 135 litres and 41% are 180 litres or greater. In the lower North Island sample (Taupo, Rotorua, Gisborne, Napier, Wanganui, Wellington, etc.) 46% are 135 litres while 44% are 180 litres or greater. In the South Island (Blenheim, Tasman, Christchurch, Oamaru, Dunedin and Invercargill) the reverse is the case, with 21% of the cylinders at 135 litres and 74% at 180 litres or greater.

It is likely that this difference in cylinder size distribution relates to policies implemented by local electricity suppliers over many years, rather than explicit consumer choice. As well as cylinder volume, the size of the elements is related to local power company policy. In some areas (notably North Island) larger (2 to 3 kW) elements were required supporting the use of smaller cylinders, while in other areas (notably South Island) lower power (possibly less than 1 kW) elements were used with larger cylinders. The variation in element size related to the load control requirements, balancing the hot water demand and line capacity.

These policies continue to have ongoing consequences, due first to the long lifetime of most hot water cylinders and second to the difficulties of replacement. Anecdotal evidence suggests that cylinders are almost invariably replaced 'like-with-like' to ensure the replacement is able to fit in the space occupied by the failed cylinder or not exceed the permitted load on the existing wiring.

Jaye et al (2001) reporting on a telephone survey of 111 craftsmen plumbers from throughout New Zealand found that respondents believed that older homes were likely to have smaller hot water cylinders set at higher temperatures to compensate for small capacity. Figure 143 examines the age distribution proportion for the 135 litre and large (greater than or equal to 180 litre) cylinders in the sample. The time period starts with the decade of the 1950s, as the sample size in the earlier decades is too small to permit a reasonable comparison. For the period from 1990, 60% of the cylinders in the sample are 180 litres or greater.

Figure 144 provides a breakdown of the different sizes of electric storage hot water systems sold in New Zealand during the 2004-05 financial year. The data are from the reports to the Energy Efficiency and Conservation Authority (EECA) required under the minimum energy performance regulations.



Source: EECA

Figure 144: NZ Sales by capacity of electric DHW cylinders 2004/5

24.9.2 Water pressure

The 'traditional' New Zealand electric hot water system is 'low pressure', based around a header tank (or more recently a pressure reducing valve) feeding an open vent cylinder (less than 3.7 m or 37 kPa head) (see Figure 194). Over time the trend has been to 'medium pressure' using a pressure-reducing-valve (generally 7.6 m or 75 kPa head), and more recently to 'mains pressure' hot water systems.

For this analysis systems with either low pressure relief valves or header tanks are counted as low pressure. Data on the cylinder or system pressure was not recorded in the early years of HEEP. In these cases, system pressures have been allocated based on available data:

- **cylinder age** – electric cylinders older than 30 years are 'low pressure'
- **cylinder photo** – cylinders marked 'low pressure' or '7.6 m head' are 'low', while cylinders marked 'mains pressure' are 'mains'
- **cylinder insulation grade** – D and C grade electric cylinders are 'low' pressure
- **system type** – instantaneous gas are 'mains' pressure
- **house exterior photograph(s)** – a roof vent pipe indicates the system is 'low', although the reliability of this method is not considered to be high as vent pipes can be left in place after a low pressure system is converted to high pressure. Therefore, this method was used as an allocation as a last resort.

After these manual allocation methods were applied, the system pressure for only 29 systems (7% of the sample) could not be categorised.

Of the houses for which pressure data are available, under three-quarters (72%) are low pressure and just over one-fifth (21%) are 'mains' pressure.

Fuel and System	Low Pressure	Mains Pressure	Unknown	TOTAL
Electric Storage	305	56	23	384
Gas Storage	11	17	6	34
Gas Instantaneous	-	20	-	20
Other	2	1	-	3
TOTAL	318	94	29	441

Table 155: System pressure by fuel type

Table 155 provides the counts for the different system types by pressure. The majority of electric storage systems are low pressure (79%), while the opposite is true for gas storage systems (32%). Figure 145 analyses the hot water system pressure by region and overall. The number of cylinders in each region is given in brackets.

Figure 145 suggests a regional pattern for the use of mains pressure systems – the further south, the greater the proportion of low-pressure cylinders. The increase is from 72% in the top of the North Island, to 79% in the lower North Island to 88% in the South Island (calculated only for cylinders for which pressure information is available).

This distribution also relates to the availability of natural gas, as mains pressure systems are more often gas fuelled (see Table 155).

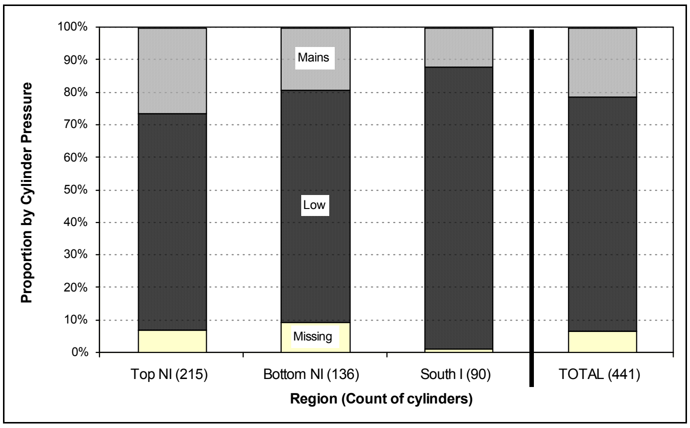


Figure 145: System pressure by region

The relationship between house age and cylinder age was also investigated. Both the year of the house construction and the year of cylinder manufacture are available for 86% of the cylinder sample (320 cylinders).

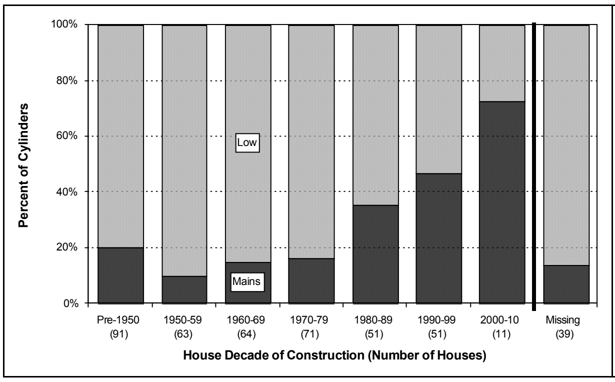


Figure 146: Pressure by house decades

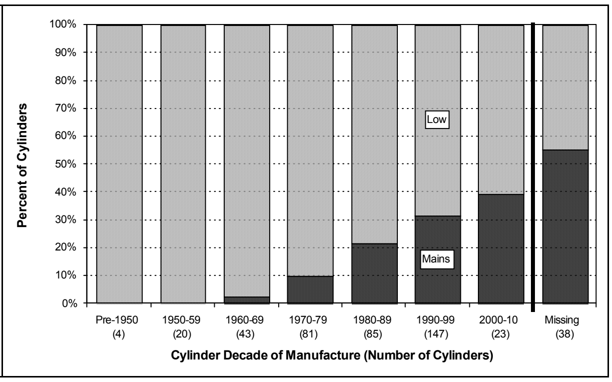


Figure 147: Pressure by cylinder decades

Figure 146 shows the distribution of hot water pressure by house decade of construction, and Figure 147 by cylinder decade of manufacture. There are no cylinders manufactured before 1930 in the sample and very few in the following two decades, so both figures start from the 1950-59 decade.

Figure 147 shows that the mains pressure cylinders found in the HEEP houses first date from the 1960-69 decade. Figure 146 suggests that there has been steady increase in the market penetration of mains pressure systems, most likely as older houses have been retrofitted from low-pressure to mains pressure systems.

24.9.3 House and cylinder age

The age of the hot water system and the age of the house appear to be of particular importance in understanding the thermal performance of the hot water system.

House age is not always easily established. In some cases, full house plans are available, while in others the house occupants may know the year of construction. In many cases it is necessary to rely on a combination of information, including the design style. The result of this is that although in some cases the exact year of construction can be established, in the majority of cases it has only been possible to allocate a decade of construction.

DHW cylinder age is also not easily established without manufacturer's documentation. Establishing the year of manufacture is based on a combination of on-site observations, notably labels giving one or more of: cylinder guarantee, date of manufacture, date of installation, or warranty expiry. In some cases an attached tag or card provides this information, but often the installation date (and hence warranty expiration) has not been noted on the cylinder during installation.

If the exact year of house construction has not been determined, for the purposes of comparison the mid-year of the decade has been used. This can lead, in a small number of cases, to cylinders appearing to be older than the house. For example, if the house was believed to have been built in the early 1970s, the decade of construction would be recorded as '1970-79' and the year of construction calculated as '1975'. If the cylinder year of construction was labelled '1970', this would make it apparently five years older than the house. Such a cylinder date would suggest that the house was actually built in 1969 or 1970, but to ensure valid comparisons the cylinder has not been used to age the house. For the purposes of analysis, these cases are taken as if the cylinder had the same decade of manufacture as the construction of the house.

The difference between the house and hot water cylinder age has been used to check for obvious errors, either in data recording or data entry.

For the purposes of allocating cylinder thermal performance, where present, the Standards 'mark' and associated standard (see Table 141) were used to categorise to the appropriate thermal performance grade, and provide an indication of the cylinder age.

Table 156 provides descriptive statistics on the electric and gas hot water cylinders in the HEEP random house sample. There are 363 cylinders using electricity and 37 using gas. Note that these may be alone, or in combination with other heat sources such as a solid fuel burner wet-back or solar water heater. Over half of the gas cylinders were over 10 years old at the time of inspection, while most electric cylinders were over 16 years old. Cylinder sizes were similar for electricity and gas, with the median volume 140 litres for electricity and 150 litres for gas.

Cylinder	Electric Storage Min	 Median	 Mean	 Max	Gas Storage Min	 Median	 Mean	 Max
Year of Manufacture	1938	1986	1983	2004	1971	1994	1991	2002
Age (years)	-	16	19	64	1	9	10	30
Volume (litres)	14	140	156	315	34	150	151	300

Table 156: HEEP random electric and gas cylinder descriptive statistics

24.9.4 Hot water cylinder age

Houses have a longer life than hot water cylinders, and it is expected that as hot water cylinders fail they will be replaced, often with the same size although not necessarily with the same pressure. Figure 146 illustrates that even very old houses (which originally would have had low-pressure systems) are being retrofitted with mains pressure hot water systems. For those houses and cylinders for which date information is available, about one-quarter (28%) of the houses (but two-thirds (63%) of the hot water cylinders) were built or manufactured since 1980. The oldest cylinder in the sample dates from the 1930s. The data does not show any obvious link between the size of cylinders in the HEEP houses and their lifetime.

Figure 148 shows the distribution of cylinders by year of construction and regional location. Nine percent of the total number could not be aged. The grouping of construction years is based on the approximate years when a significant change in cylinder thermal performance occurred (see Table 141). Most pre-1980 cylinders are ‘C’ or ‘D’ grade, and many 1980s and later cylinders are ‘B’ grade. ‘A’ grade cylinders have only been required only since 2003.

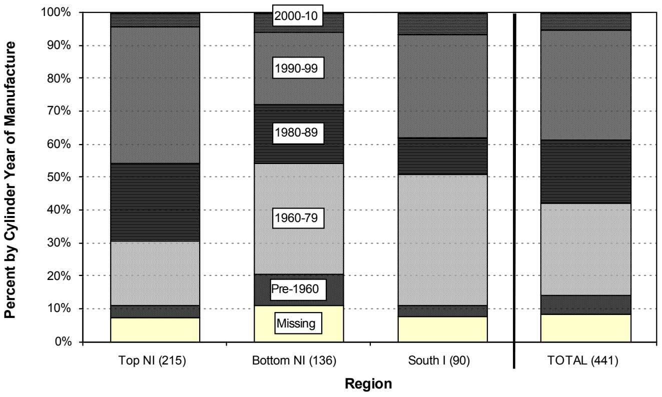


Figure 148: System age by location

Six percent of the cylinders for which both cylinder and house age are available were manufactured before 1960, 31% were manufactured in the period from 1965 to 1980, 58% from 1980 to 1999, and the remaining 6% after 2000. Figure 148 shows a regional trend, with a higher proportion of newer cylinders in the top of the North Island (75% manufactured after 1980) compared to those in the South Island (53%)

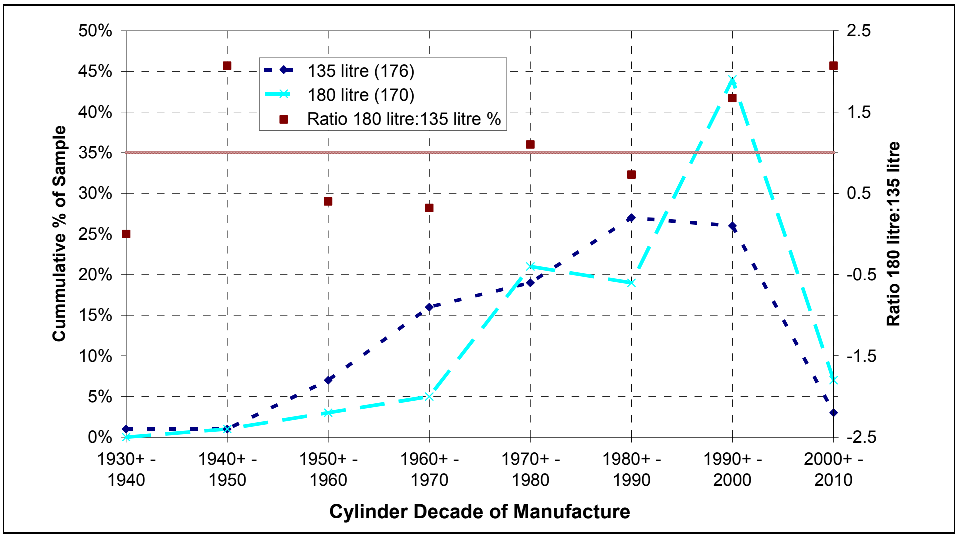


Figure 149: 135 and 180 litre cylinders by decade of manufacture

Figure 149 illustrates the age distribution by decade of manufacture for 135 and 180 litre cylinders. The curves fall off at the right hand end of the graph, as the last period is only the four years until 2004 – the last HEEP house installation – not the full 10 years as for the rest.

From the 1940s through the 1980s, 135 litre cylinders were more popular than 180 litre cylinders but during the 1990s this popularity had shifted, and now it is the 180 litre cylinder than is being used in more homes. The ratio between the percent of 135 and the percent of 180 litre cylinders is also plotted (as a small square marker) for each decade. This goes above one (i.e. the proportion of 135 litre cylinders equals the proportion of 180 litre cylinders) first in the 1970s, and then stays above it from the 1990s.

Figure 150 provides an analysis of the age of the hot water cylinder (by decade) compared to the age of the house (by decade). Figure 150 includes the 370 cases where both the decade of house construction and cylinder manufacture are available:

- just under one half (46%) of the cylinders are the same decade as the house – suggesting they were installed when the house was built
- 9% of the cylinders are only one decade younger than the house – suggesting little replacement in the first decade of life
- the remaining 45% of cylinders are two or more decades older – suggesting this is when most failures and replacements occur.

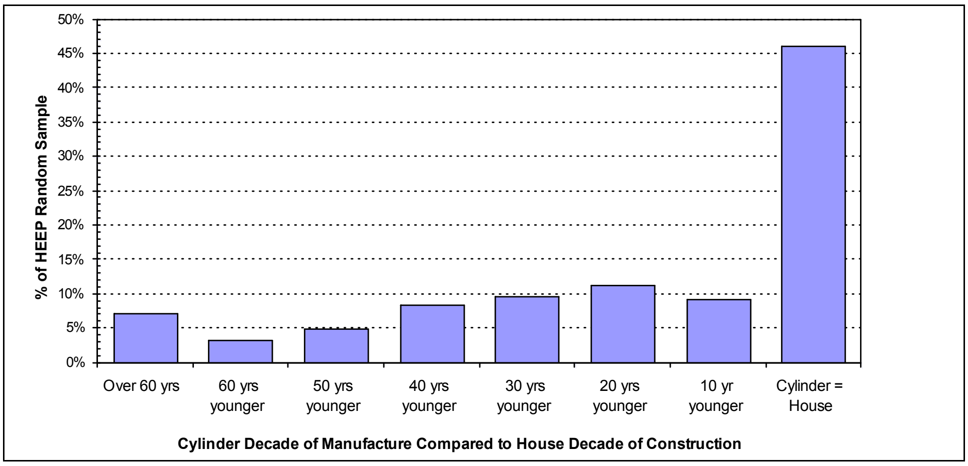


Figure 150: Cylinder manufacture compared to house construction decade

House Year	Years Ago	% of Total	Same Decade as House	Cylinder Replaced
1890-1909	96-115	5%	0%	100%
1910-1929	76-95	7%	0%	100%
1930-1949	56-75	9%	6%	94%
1950-1969	36-55	32%	26%	74%
1970-1989	16-35	32%	56%	44%
1990-2004	15-0	16%	83%	17%

Table 157: House and cylinder age comparison

On average, 46% of hot water cylinders are in the same decade as the house, but Table 157 shows this proportion varies with house age.

It was not possible to determine whether or not these cylinders were originally installed at construction, as it is feasible (albeit unlikely) that the cylinder could be replaced within the first decade of the house's life or a second-hand cylinder has been used.

Cylinder	Type	Usual Working head	Life Expectancy
Copper	Low pressure	2 – 7.6 m	20 – 50 years
Copper	Low pressure	12.2 m	20 – 40 years
Glass -lined steel	Mains pressure	35 – 50 m	12 – 20 years
Stainless steel	Mains pressure	35 – 50 m	20 – 40 years (estimate)

Table 158: Life expectancies of cylinder types

Table 158 sets out life expectancies for different cylinder types from Williamson & Clark (2001)[36]. The potentially long lifetime of older copper cylinder, low-pressure systems is supported by the results shown in the previous figures for the HEEP houses. Note that the cylinder life expectancy is affected by a range of issues specific to the house and area, notably the water quality.

24.9.5 Cylinders and house size

The physical attributes of a house (e.g. floor area, number and size of hot water cylinders) are far less flexible than the number of people that can be living in the house. Figure 151 and Figure 152 include 'instantaneous' hot water systems – these are shown as having 'zero' volume. In many cases the cylinder volume, the floor area and the number of occupants will be the same, so both figures use random 'jitter' in order not to overlay all the points.

Figure 151 compares the floor area of the monitored houses with the total volume of hot water cylinders – in houses with more than one cylinder this is the calculated total volume of all cylinders. Figure 151 suggests that designers and builders in some cases have placed some value on providing larger hot water volumes for larger houses.

Figure 152 compares the total volume of hot water storage to the number of occupants, and again there is no clear link. This would suggest that the provision of hot water designed into the house is not matching the likely number of occupants over the lifetime of the house.

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[36] Note: Table uses data originally provided by BRANZ, but is quoted from Williamson & Clark 2001.

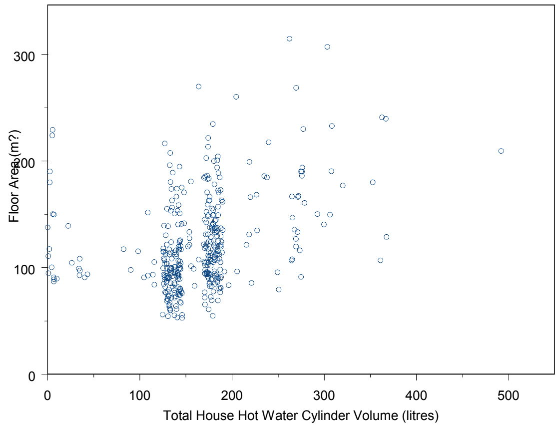


Figure 151:Total hot water volume vs. floor area

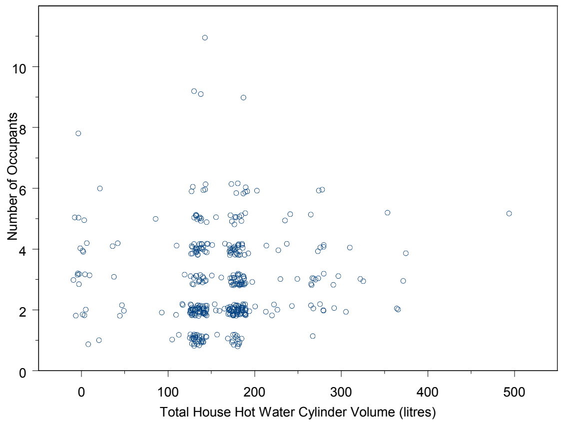


Figure 152: Total hot water volume vs. number of occupants

24.9.6 Delivery capabilities

The BRANZ Ltd *House Condition Survey* conducted in 1999 compared the size of the electric hot water cylinder to the potential household occupants (Clark et al, 2000). They calculated the potential number of people in a house as being the number of bedrooms plus one. The requirements per person were assessed at around 45 litres per day, which is a conservative average daily figure taking no account of particular occupant circumstances which could result in a much higher short-term hot water demand e.g. everyone wanting to shower at the same time. The analysis only considered surveyed houses with a single hot water cylinder but based on this calculation, it was considered that just over half of those houses had adequate electric hot water storage.

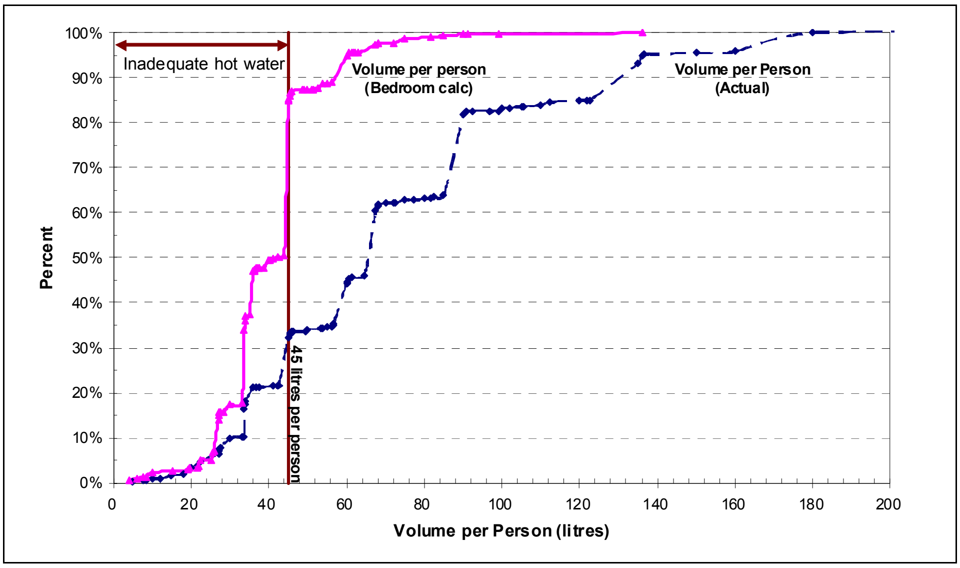


Figure 153: Single electric DHW systems – litres per person

The same analysis has been carried out for the 311 HEEP houses with one electric hot water cylinder. Figure 153 plots two cumulative-percent curves for the HEEP houses:

- the left curve (solid line) uses the same calculation method as used in the House Conditions Survey (i.e. Cylinder Volume/(Number of bedrooms + 1))
- the right curve (dashed line) is based on the actual number of people in the house (Cylinder Volume/Number of Occupants).

The curves show obvious ‘steps’ that relate to the steps in the sizes of hot water cylinders available on the market, and the discrete number of house occupants.

The calculated approach gives a similar result to that found in the 1999 house condition survey – half (50.5%) of the HEEP houses with one electric cylinder have adequate storage volume (i.e. 45 litres per occupant or greater). When the calculation is carried out using the actual number of occupants at the time of the HEEP survey, only one fifth (21.5%) of houses with only one electric cylinder have less than 45 litres per person of electric hot water cylinder storage.

There are a number of possible reasons for this difference:

- where occupants have a choice, they will limit their demand (i.e. number of occupants or the use of hot water) to match the ability of the hot water system to provide the required hot water supply
- where occupants have no choice, they may increase the hot water storage temperatures to ensure the supply matches their demand
- occupants may change their life stage faster than they change their house and hence the hot water system e.g. children grow up but the parents remain in the same house

24.10 Baths and showers

Although modern houses are likely to have both a bath and shower (and very often more than one of each) different amounts of hot water, and hence energy, are required for each. Table 159 provides design values for water temperature and volume for baths and showers (Southcorp, 2001). It suggests a ‘normal’ bath would be expected to use at least two times as much hot water as a shower, although this obviously depends on the depth of the bath, and the flow rate and length of time the shower is in use.

Appliance	Temp.	Quantity of Mixed Water	User’s Requirement
Normal bath	40°C	45-145 L	Minimum wait to fill bath to required level and ability to top up with hot water as bath water cools.
Spa bath	40°C	200-350 L	As above, with emphasis on quick filling over increased volume. A spa bath holding 300 L of mixed water would take 20 min to fill at 15 $L.min^{-1}$ flow rate.
Shower	40°C	25-70 L or more	Ability to adjust flow rate to desired or more degree varying from 7 to 30 $L.min^{-1}$ and to adjust temperature from 40°C down to ‘chill off’ temperature at will. Freedom from temperature fluctuations due to other draw-offs.

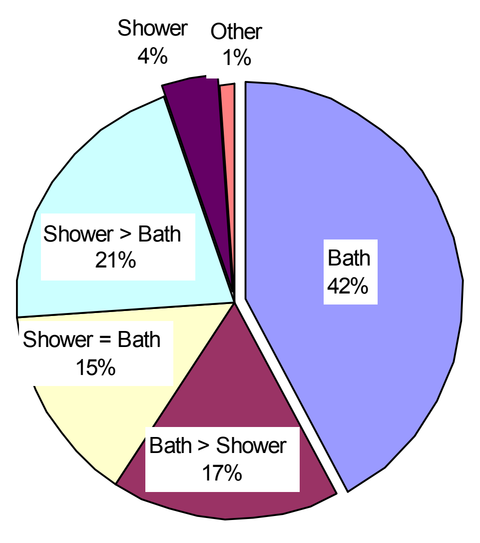
Table 159: Hot water requirements for baths and showers

24.10.1 1971/72 to 2000s

The 1971/72 Electricity Study (NZ Department of Statistics, 1973a) recorded information on the number of baths and showers in the house, and their relative use by house occupants. The results were presented comparing the number of occupants, the number of showers and baths, and their comparative usage. Data were published only for the 1,749 houses with permanently-wired electric hot water cylinders (Table 12a). Five main divisions were reported: **Bath only**; bath used more than shower (**Bath > Shower**); bath used the same amount as the shower (**Bath = Shower**); shower used more than the bath (**Shower > Bath**); and **Shower only**. A small ‘**Other**’ category includes houses that lack either a bath or a shower. For the purposes of this analysis, it has been assumed that houses with ‘only’ a shower or a bath only use only that facility.

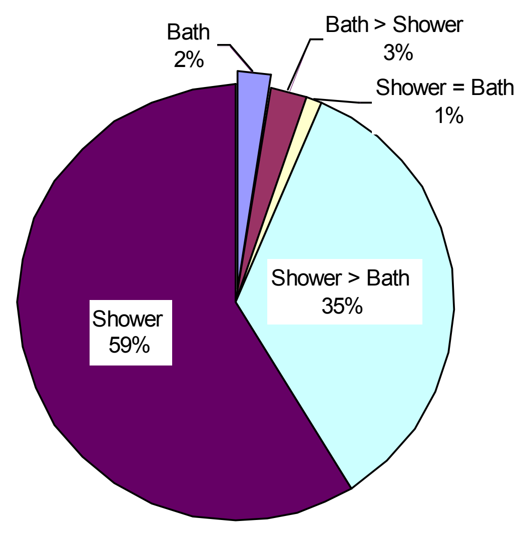
HEEP Survey section B.2 asked house occupants for information on their use of hot water. For the house, this included the number of baths, showers and shubs (small enclosed bath unit with a shower fitting). For each individual, this included their usual weekday bath or shower usage. The data on bath and shower usage are available for 385 HEEP houses.

The following two figures summarise the relative use of baths and showers for the two studies separated by approximately 30 years – Figure 154 for the 1971/72 study and Figure 155 for HEEP. For consistency, the HEEP sample has been limited to houses with one or more electric cylinders i.e. excluding houses with only gas or solid fuel hot water systems.



Data: !971/72 Household Electricity Study
(1749 houses with permanently-wired electric water heaters)

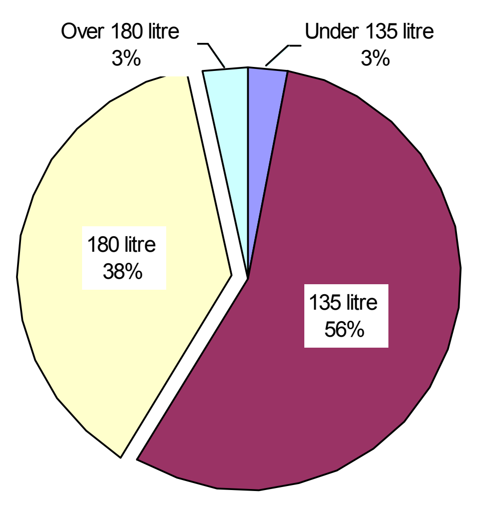
Figure 154: **Use of baths and showers 1971/72**



Data: HEEP
350 random houses with one or more electric DHW systems

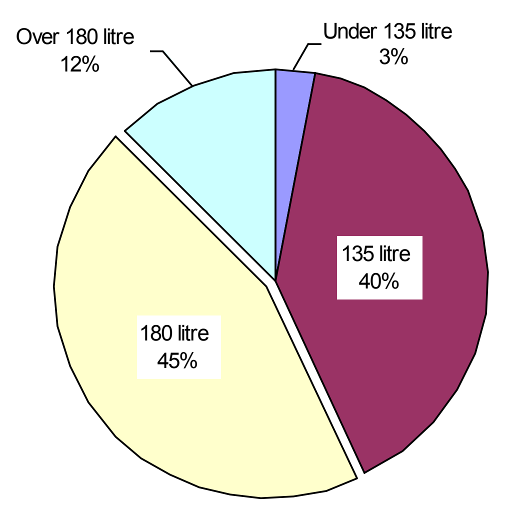
Figure 155: Use of baths and showers HEEP

Figure 154 and Figure 155 show there has been a major change in bathing habits over the past 30 years. In 1971/72, 59% of the households with one or more permanently wired electric cylinders mainly or solely used the bath. Over 30 years later, this has reduced to 2% of the HEEP houses with one or more electric storage cylinders. There has been a sizable growth in the use of showers, increasing from 25% in 1971/72 of households using the shower, or mainly the shower, to 94% in the HEEP sample.



Data: !971/72 Household Electricity Study
1,746 houses with permanently-wired electric storage water heaters

Figure 156: Household DHW volume 1971/72



Data: HEEP
346 random houses with one or more electric storage cylinders

Figure 157: Household DHW volume HEEP

Although uses of hot water have changed, it seems that hot water systems themselves have only altered slightly. Figure 156 and Figure 157 compare the total volume of house hot water electric storage cylinders for the 1971/72 study and the HEEP random houses. The houses with a total of ‘under 135 litre’ cylinder volume are in the main electric under-sink or point-of use-cylinders, which may not be the main hot water supply for the house. The proportion of smaller 135 litre cylinders has reduced from 56% to 40%, while the houses with 180 litre total cylinder volumes have increased from 38% to 45% of the sample. Houses with over 180 litres of hot water cylinders have increased from 3% to 12% over the 30 years between the studies.

There has been a 13% increase in the weighted-average size of household hot water systems – from 150 litres per household in the 1971/72 study to 170 litres in the HEEP study. Conversely, the number of people per house has reduced by 15% – from an estimated 3.4 in the 1971/72 study to a calculated 2.9 in the 346 HEEP houses which had an electric water cylinder and where data were recorded on the number of occupants.

24.10.2 Use of showers and baths

The number of self-reported showers per day per house was 2.5 ± 0.1 while the average number of showers per person per day was 0.9 ± 0.05. The self-reported average shower duration was 9.5 ± 0.2 minutes. Shower durations varied widely, as shown in Figure 158. Assuming the average flow rate of 8.4 litres per minute the average warm water consumption is 200 litres per day for showers alone.

On average the occupants reporting taking 0.4 baths per day per household, or 0.14 baths per person per day. Assuming the average bath uses 150 litres of warm water, the average daily bath warm water use is 60 litres, less than 30% of the water used for showers.

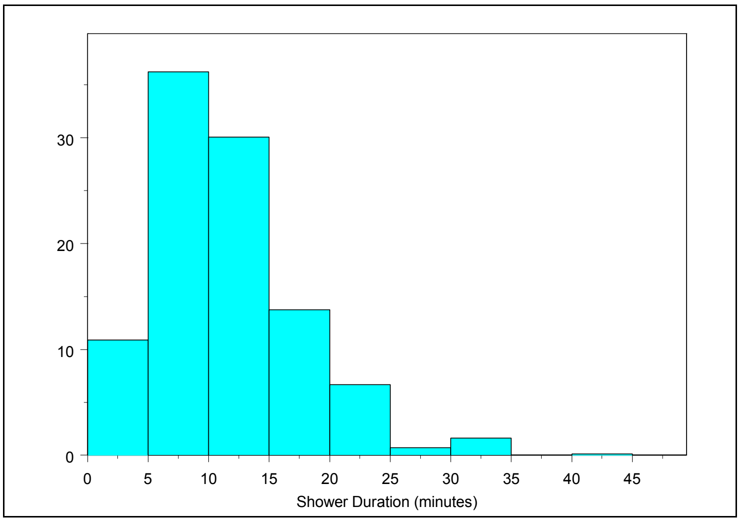


Figure 158: Self-reported shower duration – histogram

Table 160 provides information on the average use of showers by time of day. When a combination of time is given, e.g. morning and afternoon, this means the occupant had a shower in the morning and another in the afternoon.

Time of day	% Occupants bathing	# Showers per house	SE	Average shower Time per house (min/day)	SE
Morning	45%	1.7	0.1	11.2	0.6
Afternoon	4%	1.2	0.2	0.4	0.1
Evening	35%	1.3	0.1	6.4	0.5
Morning & afternoon	2%	1.6	0.4	0.2	0.1
Morning & evening	11%	2.5	0.2	2.1	0.3
Afternoon & evening	1%	1.2	0.3	0.1	-
Morning, afternoon & evening	<1%	2.1	0.8	0.1	0.1
Time of day varies	3%	1.3	0.2	0.7	0.2

Table 160: Self reported bathing times

Most occupants reported taking showers or baths in the morning and/or evening, with only about 5% taken outside these times. More showers and baths were taken in the morning than the evening.

Bathing Time	Average (min/day)	Average all NZ (min/day)	SE	% of total Shower Duration
Morning	15.1	13.6	0.7	33%
Afternoon	7.5	0.8	0.1	16%
Evening	11.7	8.6	0.6	25%
Varies	11.6	0.4	0.1	25%

Table 161: Self reported shower duration by time of day per house

The Table 160 analysis of shower duration by time of day is further summarised in to a total time per house in Table 161. Table 161 shows that on average the houses that report morning showers have longer ones than those who report use at other times of the day. Table 161 also gives average times over all New Zealand i.e. including houses that do not report showering at those times. Overall, showers are used for 13.6 minutes (58% of total shower use) in the morning, 8.6 minutes (37%) in the evening and 1.2 minutes (5%) outside these times.

24.11 Shower water flow

Although the time taken for a shower is under the control of the user, the water flow rate is established by the system in conjunction with the shower head.

The majority of New Zealand hot-water systems are low pressure, and the flow rate (as discussed later in this section) may not be high. Far higher flow rates can be obtained from mains pressure systems, in which the use of 'low flow' shower heads may a significant opportunity to improve the system energy efficiency – reducing the hot water use with the assumption that users will not increase the length of time they spend in the shower.

This was confirmed by a North American study of more than 1,100 houses in 14 cities (Mayer et al. 1999). It is expected that the large majority of these systems would be mains pressure. It was found that the average shower time increased by 25% for the low flow compared to the non-low flow showerhead, but as the flow was reduced by 53%, the total water use reduced by 66%. (See APPENDIX 8: International Review of Shower Water Flow Rates for further details).

24.11.1 Water efficiency

The water efficiency rating of a shower head relates to the water flow required to give a comfortable shower – other performance criteria such as spray spread and temperature drop are covered by AS 3662 :2005 'Performance requirements for showers for bathing'.

Table 162[37] gives the flow rates corresponding to the different ratings under AS/NZS 6400:2003 'Water efficient products – Rating and labelling', now used for the WaterMark Certification Scheme (SAI Global 2006). Measurements are based on the nominal flow rate at 250kPa, but measurements are made at 150kPa and 350kPa to determine the flow rate regulation across this pressure range. Four, five and six star ratings are not available.

Rating	Old Descriptions		Flow rate
			Over 16 L.min^{-1}
*	A	Good	> 12 L.min^{-1}
**	AA	High	> 9 L.min^{-1}
***	AAA	Very high	> 7.5 L.min^{-1}

Table 162: Shower flow ratings

Although the HEEP survey attempted to find information on the presence or absence of low-flow shower heads, the occupants very seldom had such detailed knowledge. This problem was also found in a water use study in Perth, Western Australia (Loh & Coghlan 2003).

24.11.2 Measured shower flows

The HEEP audit included measurement of the shower flow rates for each shower. HEEP did not measure the water pressure, nor was the shower control type recorded (e.g. separate hot and cold taps, mixing valve with or without flow control).

Table 163 provides summary statistics on shower water flows by water temperature and pressure for the randomly selected HEEP houses. The 'cold' and 'hot' water temperatures were established either by turning on only the appropriate tap, or with continuous flow mixers turning to the highest flow position at the appropriate end of the dial. 'Warm' was a mixture of hot and cold water at a suitable temperature (judged by the person undertaking the

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[37] See also www.watermark.standards.org.au, Water Services Association of Australia www.wsaa.asn.au and the Water Corporation of Western Australia www.watercorporation.com.au,

Temperature	Pressure	Number in sample	Average flow rate (L.min^{-1})	Flow standard deviation
Cold	Low	336	6.1	0.2
	Mains	121	11	0.6
	Average	490	7.5	0.2
Warm	Low	331	6.9	0.2
	Mains	119	12.5	0.5
	Average	483	8.4	0.2
Hot	Low	331	4.7	0.1
	Mains	118	10.1	0.5
	Average	481	6.2	0.2

Table 163: HEEP shower flow by water pressure and temperature

Table 164 gives the minimum and maximum water flows for the different cylinder pressures. As some shower mixers have limits on the maximum hot-only and/or cold-only flow, these measurements may not represent the achievable flow from the hot water system.

The maximum recorded cold water flow rate was 33 L.min^{-1}. The maximum flow (for any water temperature) for mains pressure DHW system was 30 L.min^{-1} and 20 L.min^{-1} for low pressure system. On average, 19% of low pressure systems had 'warm' shower flows over 9 L.min^{-1}, while 72% of mains pressure systems were above this threshold.

Cylinder pressure	Maximum flow (L.min^{-1})		Minimum flow (L.min^{-1})	
	Hot	Warm	Hot	Warm
Mains	26.4	30	2	2.7
Low Pressure	13.6	20	0.9	1.3
Not recorded	18	20	3	2.7

Table 164: Maximum & minimum water flows

Table 165 provides an analysis of the warm water flow rates for the approximately 450 showers for which system pressure information was available, divided into the star categories given in Table 162 – note that the higher number of stars the more efficient (lower flow) the shower head provided it is delivering an acceptable shower quality. A separate category has been used for under 5 L.min^{-1}, and the three-star category in Table 165 limited to water flows from 5 to 9 L.min^{-1}

Description	WMCS	Mains	Low	TOTAL
Very low flow (< 5 L.min^{-1})	< 5 l/m	8%	29%	23%
Low flow (5 - 9 L.min^{-1})	*** or better	20%	52%	44%
High flow (9 + L.min^{-1})	** or worse	72%	19%	33%

Table 165: HEEP Shower warm flow rates by WMCS rating

Table 165 shows that although about one half (52%) of the low pressure showers deliver warm water at a WMCS rating of three stars or better, this is the case for only one fifth (20%) of the mains pressure systems. Overall, more than two thirds (67%) of New Zealand showers are already at three stars or better – but this is driven by the high proportion of low pressure systems.

24.11.3 Impact of reducing shower flows

Mains pressure systems are being increasingly used (see Section 24.9.2), so planning must not be on the basis of average shower flow rates, but the higher mains pressure shower flow rates.

What would be the consequences of changing the shower heads measured with a flow over 9 L.min^{-1} to a 6 L.min^{-1} 'low flow' shower head?

Table 166 shows that this would result in a reduction in the average flow rate for low pressure systems (including those that have not been retrofitted) of 1 L.min^{-1} and by 6.4 L.min^{-1} for the mains pressure systems.

Pressure	Average 'warm' flow		Average after retrofit	
	Flow (L.min^{-1})	Standard deviation	Flow (L.min^{-1})	Standard deviation
Low	6.9	0.2	5.9	0.1
Mains	12.5	0.5	6.1	0.1

Table 166: Effect on average flows from retrofitting 'low flow' shower heads

However, Table 166 disguises the impact of the reduction in flow rates on individual houses. For houses with a shower flow above 9 L.min^{-1}, the average flow reduction would be 8.6 L.min^{-1} for a mains pressure system and 5 L.min^{-1} for a low pressure system. This would have a significant impact not only the use of water and the energy required to heat the water, but also on the need to maintain excessively high water storage temperatures in inadequately sized low pressure hot water cylinders.

Charges per cubic meter Auckland region	Base $/m³	% of freshwater subject to charge	Effective $/m³
Metrowater Network fresh water	1.288	100%	1.288
Metrowater Network waste water	3.08	75%	2.31
Total water charges			3.60

Table 167: Auckland water costs (1 Sept 2006)

Table 167 lists the current water charges for the Auckland region per cubic metre (1,000 litres)[38]. The annual service charge of $65.80 ($0.18 per day) has not been included in the analysis. Waste water charges are based on 75% of the freshwater volume – thus for each litre of water consumed the cost is 0.36 cents ($0.0036 $/litre). All costs include GST.

Thus for a house in Auckland with a shower flow of 18 L.min^{-1} which switched to a 9 L.min^{-1} shower head (saving 9 L.min^{-1}) and maintained a 5 minute shower, the **water savings would be around 16.2 cents per shower** (5 min x 9 L.min^{-1} x 0.36 c/litre).

With a reduced flow (freshwater and waste water), based on heating the water from 14°C to 39°C and an electricity tariff of 17.7 cents per kWh[39], the **energy savings would be 18 cents per shower**. The daily electricity supply charge of $0.909 has not been included.

The total savings would be approximately **34 cents per shower**, or over a full year $124 assuming one shower per day. Thus for a shower with a water flow of 13 L.min^{-1}, the retrofitting of a low-cost, low-flow shower head (product cost approximately $40), would have a payback of three months with one shower a day.

24.12 Water temperatures

As part of the HEEP monitoring equipment installation, the hot water tap temperature was measured at the tap closest to the hot water cylinder. The hot water was allowed to run until the temperature was considered to be stable, and then it was then read using a digital

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[38] Price source: http://www.metrowater.co.nz/yourbill/residential_charges.aspx Accessed Apr 2007.

[39] Electric prices from http://www.consumer.org.nz/powerswitch/default.asp 5 April 2007 for Mercury Energy Standard User tariff.

thermometer. Either a Dick Smith Electronics ‘Digital Pocket Thermometer’ or ‘Digital Stem Thermometer’ was used. These have resolutions of 0.1°C and a claimed accuracy of ± 1°C. Calibration testing was undertaken, and correction curves prepared. The reported water temperatures have now been corrected for publication.

Previous research has found that New Zealand home hot water temperatures are higher than in other countries (Waller, Clarke & Langley 1993). HEEP data can be used to help understand the factors that determine hot water temperatures in New Zealand houses.

24.12.1 Water temperatures by fuel type

Figure 159 provides histograms for the temperature distributions for the four largest groups of hot water systems – electric storage, electric storage plus solid fuel (wetback), gas storage and instantaneous gas.

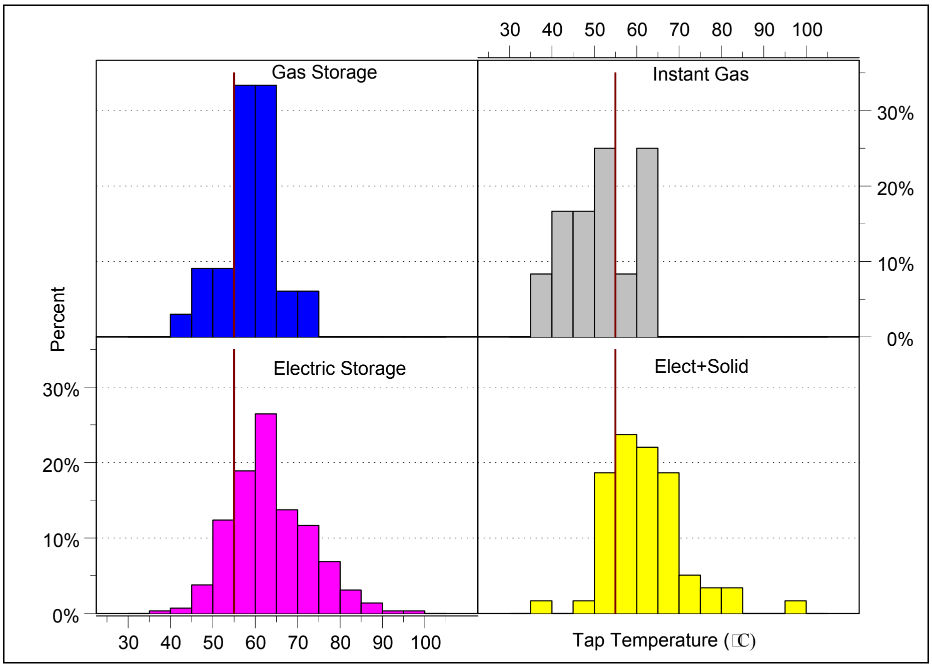

Figure 159: Tap temperature by system type

It can be seen that in a sizeable proportion of all the system types tap temperatures are over 55°C (marked by a vertical reference line). Overall all the systems, 80% of the measured tap temperatures were above 55°C while only 59% were above 60°C. Given the high proportion of electric storage systems, it could be expected that these would drive this statistic.

	Electric Storage	Electric + Solid	Gas Storage	Gas Instant	TOTAL
TOTAL DHW	314	63	34	20	441
Total with temp available	292	59	33	12	403
Count >55 °C	241	46	26	4	321
%	83%	78%	79%	33%	80%
Count >60 °C	186	32	15	3	239
%	64%	54%	45%	25%	59%

Table 168: High tap temperatures by system type

Table 168 tabulates for electric storage, electric storage with solid fuel (wetback), gas storage, gas instantaneous and total overall systems the number of each type in the HEEP sample for which tap temperatures are available and the number and percent for which tap temperatures are over 55°C and 60°C.

Around 80% of the storage systems (electric or gas) had tap temperatures over 55°C, but only 33% of the instantaneous systems. 64% of electric storage but only 45% of gas storage and 25% of gas instantaneous systems delivered tap water at a temperature over 60°C. A t-test comparison of electric and gas storage systems (excludes wetback and instantaneous) suggests these are two different distributions (t = 3.5361, p-value = 0.0009), and similarly a electric and gas fuel comparison suggests different distributions (t = 4.8736, p-value = 0).

24.12.2 Water temperatures by cylinder size

Table 169 provides descriptive statistics for 135 and 180 litre cylinders (all fuel types) based on the measured temperature at the tap nearest to the cylinder. Electricity dominates, fuelling 90% of the 135 litre and 93% of the 180 litre cylinders.

	Min	Median	Mean	Max
135 litre	36°C	63°C	64°C	88°C
180 litre	22°C	60°C	61°C	99°C

Table 169: HEEP 135 and 180 litre cylinder statistics

Figure 160 shows the temperature distribution for electric 135 and 180 litre cylinders, both as ‘bell’ curves. The numbers of each cylinder size are given in brackets. The two cylinder sizes have statistically different temperature distributions (t=2.93, p-value 0.0036), with the mean temperature at 64°C for the 135 litre cylinders and 61°C for the 180 litre cylinders. Extremely high water temperatures were usually found to be due to a faulty thermostat.

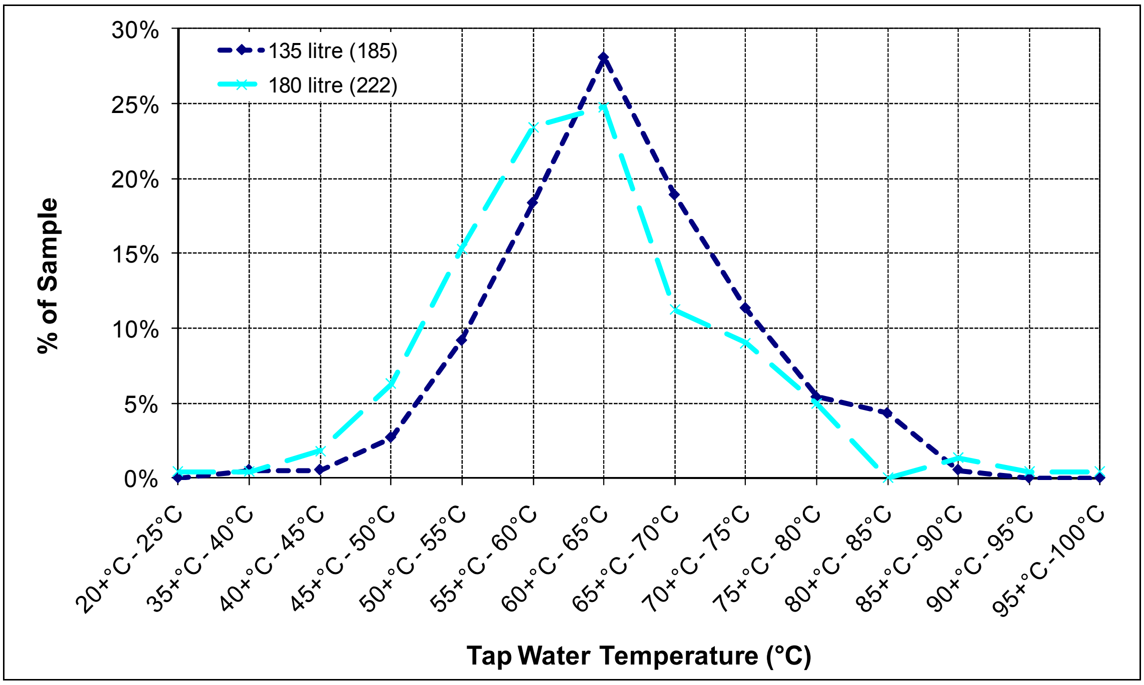

Figure 160: Distribution of hot water tap temperature by electric cylinder volume

It should be noted that this does not mean larger cylinders always have safe maximum temperatures, as is shown by the maximum tap temperatures in Table 169. Tap temperatures above 65°C are found in 41% of the 135 litre cylinders and 27% of the 180 litre cylinders. Thus about one in four of the 180 litre cylinders have even more dangerously high water temperatures, compared with more than two out of every five of the 135 litre cylinders.

The HEEP temperature measurements were taken at taps as close as possible to the hot water cylinder. In many cases this was in either the laundry or kitchen. Since 1993 it has been a requirement under the New Zealand Building Code Clause G12 to install a mechanism to limit tap temperature (e.g. a 'tempering valve') on the supply to any 'sanitary fixture used for personal hygiene' (see Section (see Section 24.3.1). It is possible that some tempering valve installations permit water to be delivered at cylinder temperature to the laundry or the kitchen sink, as these are not considered to be 'sanitary fixtures'. The presence, or absence, of a tempering valve was recorded for 462 out of the 530 hot water systems. Of these, 16% of these had a tempering valve fitted.

The HEEP installation also measured the hot water temperature at the shower. A comparison of the 'tap' and 'shower' hot water temperatures for the 70 houses which had a tempering valves, and in which both shower and tap temperatures were available, found 10 houses (14% of the sample) where the water supplied to the tap nearest the hot water cylinder (often the laundry sink) could be by-passing the tempering valve. In 17 cases (24%) there was a tempering valve present, and the temperature delivered at the tap nearest to the cylinder was greater than 60°C.

For the cylinders 'lacking' a tempering valve (i.e. none was found in inspection of the hot water cupboard), in 37% of cases the nearest tap was more than 5°C hotter than the shower – with the majority of these ranging from 5°C to 25°C hotter. For two-thirds (66%) of these cylinders, tap water temperature was over 60°C. This suggests that in at least some cases there was an over-temperature control within the shower mixer.

Just under one-third (32%) of the measured shower hot water temperatures were above 60°C, one in 12 (8%) were over 70°C, and 1% were over 80°C.

24.12.3 Electric thermostats

A thermostat is a device that senses temperature and reacts at preset temperatures to turn a power supply on or off (Williamson & Clark, 2001). Water heating thermostats are designed to regulate the supply of energy to the element and thereby maintain the water temperature within predetermined limits. The two main types of thermostat used with hot water cylinders in New Zealand are:

- **rod type**: usually concealed within the element box, it is not easily accessible to the householder. It is usually set during installation by the electrician, and requires the removal of the cover plate and the use of a screwdriver to change the setting. "Rod type thermostats appear in many older cylinders and are not noted for their accuracy" (Williamson & Clark 2001). It is possible to replace rod type thermostats with capillary type thermostats.
- **capillary:** consumer-adjustable thermostats are generally based on a capillary type thermostat that "are generally regarded as more accurate and more reliable than rod type thermostats" (Williamson & Clark 2001). The control knob is usually on the outside of the element box, readily accessible to the user. This style of thermostat is covered by New Zealand Standard **NZS 6214:1988:** *Thermostats and thermal cut outs for domestic thermal storage electric water heaters (alternating current only).*

The inaccuracy of rod type thermostats has long been known, but HEEP provides the first data on actual performance in-use. The HEEP data are now able to be used to remedy this deficiency, considering both the age of thermostat and the general error.

As the common rod type, immersion thermostats are not marked with the date of manufacture, so it is difficult to examine their reliability over time.

New Zealand completed conversion to the SI (metric) system in 1976 (McLauchlan, 1989), when temperatures stopped being monitored in units of Fahrenheit (°F) and shifted to Celsius (°C). Although existing stock continued to be sold, a reasonable assumption is that if a thermostat is marked in Fahrenheit it is of at least this age.

The HEEP survey recorded thermostat settings in the units given on the thermostat, and then converted to Celsius during processing. A flag was set during the data entry to record if the thermostat was marked in Fahrenheit or Celsius. For 30 of the thermostats the units of temperature marks were not recorded, giving 427 for which the temperature units were recorded. Seventy thermostats had markings in Fahrenheit (16% of the cylinders for which this was recorded).

Glass-lined, mains pressure cylinders are designed to operate to a maximum temperature of 70°C to 82°C depending on the vitreous-enamel lining (Southcorp, 2001). All valve-vented cylinders are required to be fitted with an over-temperature cut-out as a safety device should the primary thermostat fail.

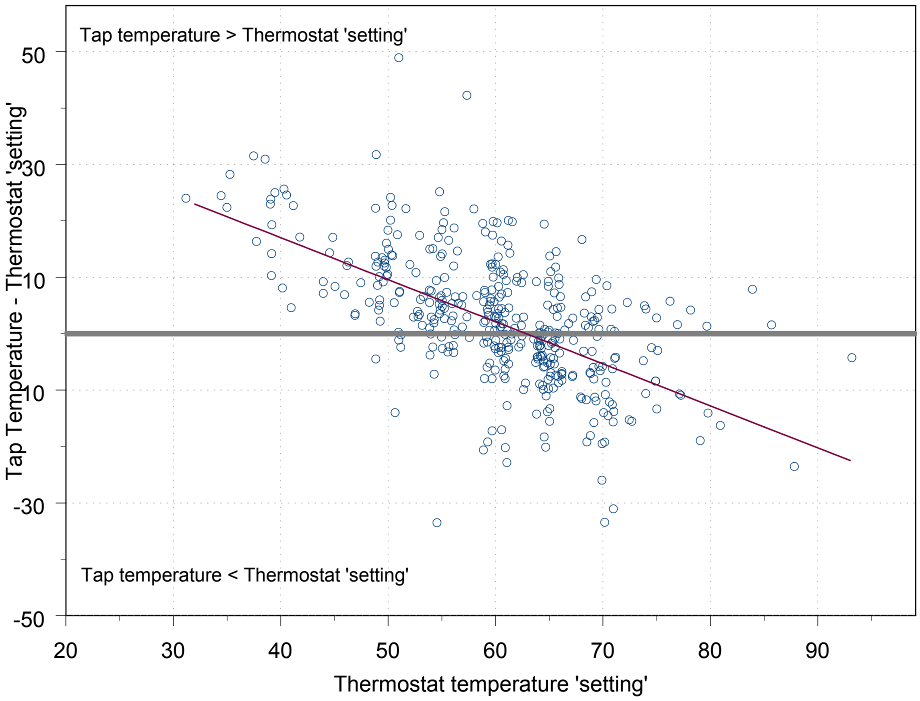

Figure 161: Variation between thermostat setting & delivered water temperature

Figure 161 plots the thermostat set temperature (x-axis) and the difference between the thermostat set temperature and the actual delivered temperature at the tap nearest to the hot water cylinder (y-axis), for the 398 electric cylinders for which both tap and thermostat setting temperatures were available.

If thermostat settings were perfectly matched to the tap temperatures, the points would all fall on the zero horizontal line (i.e. Tap Temperature = Thermostat Temperature), but this is clearly not the case. Only in 9% of the cases is the tap temperature within ±1°C of the thermostat temperature, 36% are within ±5°C and 66% are within ±10°C.

A linear regression found a reasonable relationship ($r^2 = 34\%$) centred around 61°C (red line in Figure 161), but it can be seen that there is a wide spread of temperature differences.

One-quarter (25%) of the thermostats read more than 5°C hotter than the water at the tap (i.e. tap cooler than thermostat), but over one-third (39%) of the thermostats read 5°C cooler than the tap (i.e. tap hotter than thermostat). In 22% of the cylinders the tap was more than 10°C hotter than the thermostat reading, but only in 7% of the cylinders was the tap was more than 20°C warmer and in 2% the tap was less than 20°C cooler than the thermostat.

The distribution of the temperature differences in Figure 161 is close to a normal distribution (skewness = 0.17), and with a sample standard deviation of 11.2°C. This is somewhat higher than would be desirable, and reflects the inability of rod type thermostats to provide good temperature control.

When the thermostats are separated into temperature markings (°F assumed to be pre-1976), they have different intercepts – 64°C ($r^2 = 44\%$) for those marked in °F and 61°C ($r^2 = 32\%$) in °C. A t-test suggests these are two different distributions (t=4.33, p-value 0). This would suggest that older rod type thermostats deliver hotter water than the newer versions.

24.12.4 How hot?

The hot water system largely establishes the hot water supplies that will be available to the household. The cylinder volume (if a storage cylinder), the distribution piping or the electric element size can only be altered by specialists. A larger cylinder, improved distribution pipes, a larger electric element or a completely new system and fuel (e.g. change from a small electric storage cylinder to an instantaneous gas system) requires sizeable capital expenditure and the expert skills of an electrician and/or plumber.

The only part of the hot water system that most householders can readily alter is the thermostat (even if not a consumer-adjustable design). The amount of energy stored in the hot water cylinder is directly related to the cylinder volume and water temperature.

For example, the total energy stored in 135 litres of water at 75°C (42 GJ) is almost exactly the same as the energy stored in 180 litres of water at 55°C (41 GJ)[40]. The useful 'hot' water is that above body temperature (37°C), and this changes the relationship. The 135 litre cylinder at 75°C actually holds nearly 60% more useful hot water than the 180 litre cylinder at 55°C (22 GJ compared to 14 GJ)[41]. The 135 litre cylinder at a dangerously hot 75°C is equivalent to a cylinder twice as large (270 litre) at a safe water temperature of 55°C.

One consequence of the unsafe, higher water temperatures is an increased chance of skin burns[42].

The drive for adequate warm water for showers has been shown in some circumstances to overcome safety considerations:

- Tustin (1991) reported on a Whakatane project where 12 households were provided with consumer adjustable thermostats on their hot water systems. At the time of installation these were set to 55°C and the residents were told about safe water temperatures. On returning to the houses after one year it was found that 25% of households had adjusted the thermostat upwards (i.e. greater than 60°C) to avoid running out of hot water.
- A Bay of Plenty retrofit programme found that after a range of energy-efficiency options had been installed (including low flow shower heads to reduce hot water

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[40] The Specific Heat of water at 40°C (the energy to raise one litre by 1°C) is 4.1786 $MJ.l^{-1}.°C^{-1}$.

[41] For water stored at 37°C, the 135 litre cylinder contains 21 GJ while the 180 litre contains 28 GJ

[42] Further research on hot water is available from the Injury Prevention Unit at the University of Otago (www.otago.ac.nz/ipru). Safekids provide information on safety with hot water (www.safekids.org.nz).

demand) and thermostats were turned down, only a few houses increased the thermostat settings (Jo Hunt – Energy Options Ltd, pers. com. 2003).

Figure 162 gives the exposure time needed for hot water to cause full thickness epidermal burns of adult skin at various water temperatures (Katcher, 1981 adapted by Waller, Clarke & Langley, 1993). Hot water is more dangerous to the very young and the elderly, whose skin is less able to withstand higher temperatures. For a child placing their skin into water at 54°C, only 10 seconds is required for a full-depth burn, compared with 30 seconds for an adult (Feldman 1983).

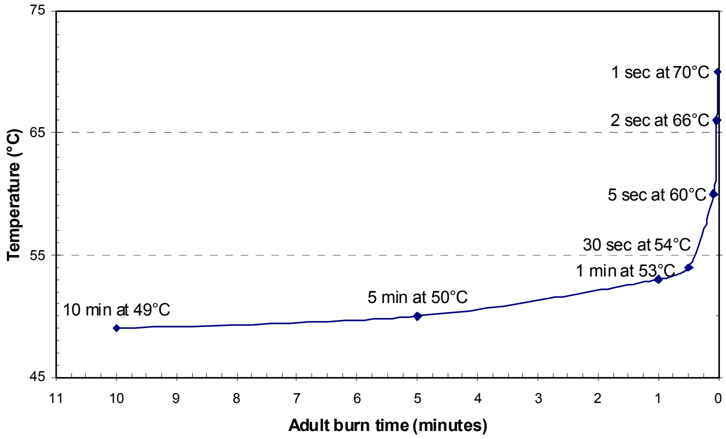


Figure 162: Adult skin (full thickness) epidermal burn time

Turning down thermostats may result in short-term benefits (both safety and energy efficiency), but unless the system provides adequate hot water to meet the needs of the house occupants, the thermostat may eventually be turned up. Such campaigns also do not consider the poor performance of most electric hot water cylinder thermostats, and this may be even more critical to reducing the opportunity for hot water burns. It also needs to be recognised that only the use of correctly operating tempering valves or upper-limit controlled and fail-safe thermostats can ensure that unsafe temperatures are not possible.

Figure 163 compares the nearest tap hot water temperature with the average age of the house occupants. There is no significant relationship.

No link was found with the age of the youngest or the oldest person and hot water temperature, suggesting that age is no barrier to the provision of dangerously hot water.

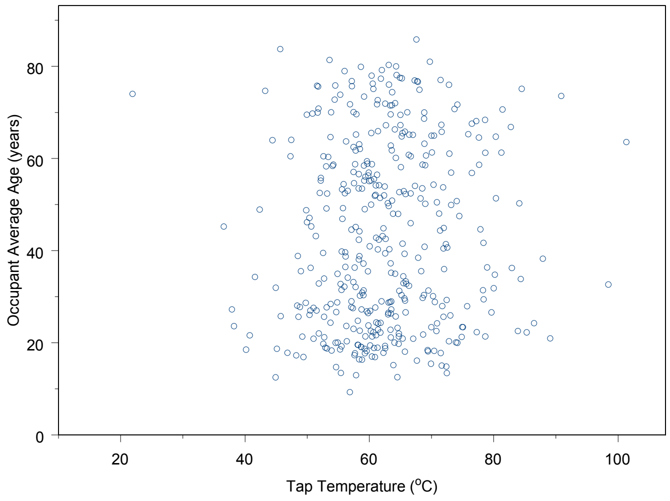
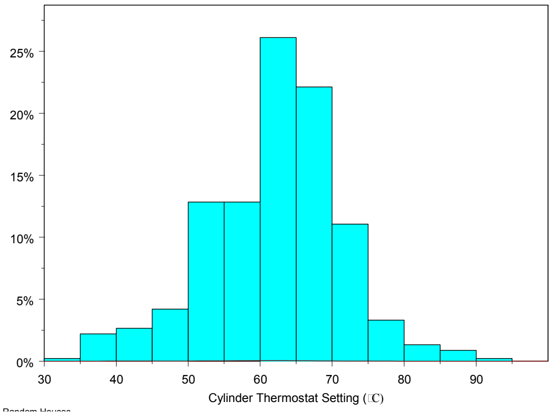


Figure 163: Hot water temperature vs. occupant average age

Figure 164 gives the thermostat setting distribution, and Figure 165 the tap temperature distribution for the randomly selected HEEP houses. As gas hot water systems tend not to have the thermostat marked by temperature, the 452 cylinders in Figure 164 include only 6% that are not electric. The 489 cylinders in Figure 165 include all hot water systems for which a tap temperature has been measured.

The median for the thermostat setting is 60°C and for the tap temperature it is 62°C. However, the thermostat distribution has a skew of -0.2 (i.e. is asymmetric towards lower thermostat settings), and the tap temperature distribution skew is +0.2 (i.e. asymmetric towards the higher delivered water temperatures).



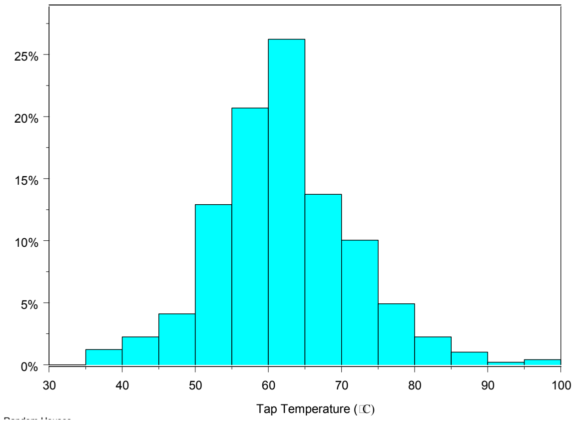


Figure 164: Thermostat setting distribution **Figure 165: Tap temperature distribution**

Figure 166 gives thermostat settings and nearest tap water temperatures for 405 electric hot water cylinders in the randomly selected HEEP houses. Tap temperatures were not recorded for 22 other electric hot water cylinders. Temperature and thermostat data were recorded during the HEEP installation. This involved an inspection of the hot water cylinder and its surroundings, and the measurement of water temperatures at the tap nearest to the cylinder once maximum temperature had been reached. In a small number of houses, a recent large draw-off of water resulted in a water temperature that was obviously low. Each point in Figure 166 is one cylinder, with solid markers showing a tempering valve is present.

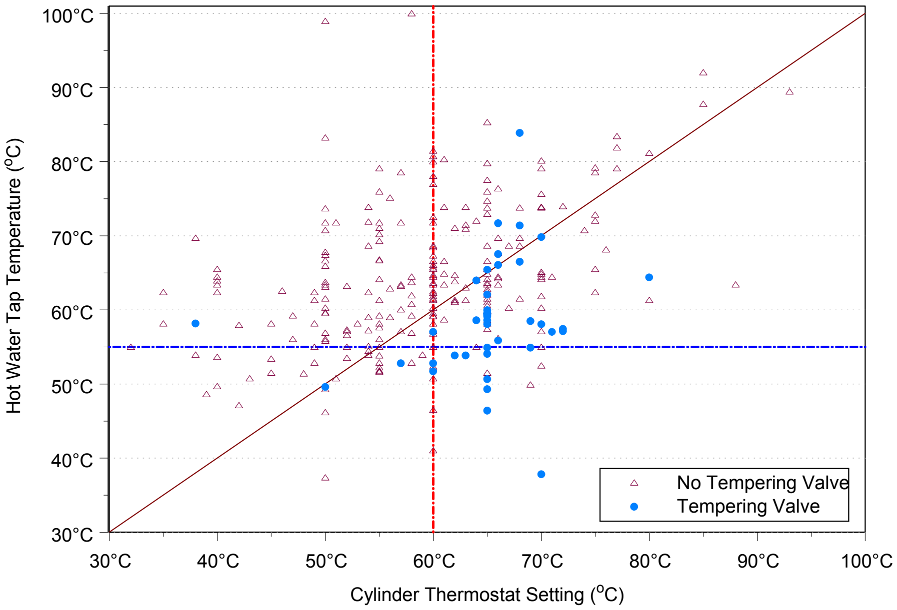


Figure 166: Thermostat setting vs. tap hot water temperature

Tap Temperature	Cylinder Thermostat Setting Up to 55°C	 55 - 60°C	 Over 60°C	TOTAL
Up to 55°C	9%	5%	6%	20%
55 - 60°C	8%	4%	9%	20%
Over 60°C	13%	15%	32%	60%
TOTAL	30%	24%	46%	100%

Table 170: Count of thermostat setting vs. tap hot water temperature

Table 170 summarises Figure 166, and reports that 80% of hot water cylinders delivered water at temperatures over 55°C (i.e. dangerously hot). Figure 161 illustrated that the thermostat setting can bear little resemblance to the actual water temperature, so the thermostat settings only provide an indication of the house occupants' expectations. Note in Figure 166 that in four cases tap water is delivered at close to or over 90°C.

Table 135 set out the requirements of the New Zealand Building Code Clause G12 'Water Supplies', which in brief require the use of a tempering valve to permit hot water storage to be above 60°C and water delivery to be below 55°C.

The vertical (thermostat > 60°C) and horizontal (delivered water <55°C) dotted lines on Figure 166 illustrate these two constraints for housing. The sloped line in Figure 166 illustrates the expected situation if a tempering valve was not present – the temperature of the delivered water would equal the thermostat setting (assuming perfect operation of the thermostat).

Figure 166, together with the other analysis reported here, raises a number of health and safety issues about the provision of hot water from domestic electric hot water cylinders:

- **Eight out of every ten cylinders delivered water at temperatures UNACCEPTABLE to the NZBC:** 80% of all the measured tap temperatures were above 55°C, but the temperature was above 55°C for 83% of those without a tempering valve and 67% for those with a tempering valve. Table 171 provides summary statistics for the 382 cylinders for which tempering valve information was available. The high proportion of tap temperatures between 55°C and 60°C should be noted. In addition, in some cases shower controls incorporated a temperature limiting device, but even so 32% of the 'hot' shower temperatures were above 60°C.

Tap Temperature	Tempering Valve	No Tempering Valve	Total
< 55°C	33%	17%	20%
55-60°C	43%	17%	21%
> 60°C	24%	66%	59%
TOTAL	100%	100%	100%

Table 171: Tap Temperature and use of tempering valve

- **One-third of the cylinders had INACCURATE thermostat control:** Only two thirds (66%) of the delivered water temperatures are within ± 10°C of the thermostat setting. 22% delivered water at temperatures more than 10°C higher than the thermostat setting, including 7% that delivered at more than 20 °C higher than the thermostat – in other words even if occupants set the thermostat to what they believe to be a 'safe temperature', 22% of the time the tap temperature will be dangerously hot.
- **OLD THERMOSTATS are less accurate than newer ones:** 60% of thermostats marked in Fahrenheit (i.e. most likely made prior to 1975) delivered water more than 5°C warmer than the setting, compared to 35% of those marked in Celsius. 12% of those marked in Fahrenheit delivered water 20 °C higher than their setting compared to only 6% for those marked in Celsius. Rod type thermostats are long lived, with 16% of the sample marked in Fahrenheit – suggesting a minimum life of longer than 25 years.
- **One-third of the thermostats set at a SAFE TEMPERATURE delivered UNSAFE hot water:** In the total sample 40% of cylinders had the thermostat set at 60°C or under, but about one third of these (15% of the total) had water over 60°C being delivered at the tap. Thus, even if the occupants attempted to ensure safe temperature water was delivered through correct setting of the thermostat, the thermostat was not providing it.
- **One out of four houses with a TEMPERING VALVE delivered hot water over 60°C**: Only 16% of the cylinders (for which thermostat and water temperature data was available) had tempering valves to ensure water would be delivered at a 'safe' temperature. Of these systems, 33% were delivering water at less than 55°C, 43% between 55°C and 60°C, and 24% at a temperature above 60°C – although the maximum measured hot water delivery temperature for a cylinder with a tempering valve was only 84°C, compared to the maximum of 100°C for one electric storage system without one.

These results help to identify potentially important hot water health and safety issues in New Zealand homes. The HEEP data could be used to develop a range of tools to assist in the development of electric domestic hot water safety programmes.

24.13 Improving cylinder thermal performance

This section uses HEEP data to investigate the question: What would be the 'actual' benefit of insulating existing hot water cylinders to the level required in NZBC H1 2000?

For the purposes of this investigation, any DHW energy efficiency improvement is assumed to have no takeback (i.e. no more hot water is used than was previously the case), so all the 'savings' would be reflected in energy use or GHG emission reductions.

A few houses have more than one hot water system (see section 24.5), but the results are here reported on a per house basis. The characteristics per cylinder are very similar to the per-house values, and have not been reported. An average house uses around 485 litres of water per day (Waitakere City Sustainable Home Guidelines 2002), while HEEP measurements suggest around 160 litres of this are taken from the cylinder as hot water per

Large reductions in energy use and GHG emissions can be achieved by upgrading hot water systems, and by reducing hot water consumption. EECA's Energy Saver Fund and Residential Grants Programme have implemented a range of improvements to hot water systems, which include cylinder wraps, pipe insulation and low-flow shower heads. The projects have been run by various interested groups including community groups, local energy trusts and power/lines companies, and commercial companies. The energy reductions claimed are substantial, but no monitoring data has been published.

To calculate the impact from upgrading the hot water cylinder thermal performance, a number of factors must be examined or estimated:

- costs of retrofit
- energy use and costs before and after upgrade
- GHG emissions before and after upgrade
- lifetime of upgrade and lifetime of system if the upgrade was not put in place.

24.14 Costs

This section reviews costs for cylinder wraps, electricity, Greenhouse gas emissions (GHG) and scrap potential for old copper low pressure cylinders.

24.14.1.1 Cylinder wraps

There are a number of electric hot water cylinder wraps available commercially. The installed price of a wool cylinder wrap from Negawatt resources is of the order of $150 including GST if installed with other activities, or $89.95 inc GST for the wrap alone[43]. This cylinder wrap is manufactured from wool insulation with a calico backing.


Figure 167: Negawatt cylinder wrap

Other suppliers include Mitre10 which sells a 50 mm thick fibreglass cylinder wrap for $64 inc GST[44] and Bunnings (Autex Eco Wrap) polyester blanket which retails at about $48 inc GST[45] Other products may also be available.

For the purpose of this analysis an installed cost of $150 has been used.

24.14.1.2 Electricity Costs

As at 15 February 2007, the average weighted retail electricity prices of incumbent retailers for domestic customers was 20.37 c/kWh, with prices ranging from 16.50 c/kWh for an Auckland retailer to 28.54 c/kWh for a West Coast retailer (MED 2007). Price discounts for houses with rippled controlled hot water are around 5%, and for separately metered night rate systems, up to about 50%.

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[43] www.negawatt.co.nz accessed 7 August 2007 and phone enquiry.

[44] www.mitre10.co.nz accessed 24 July 2007

[45] Bunnings Porirua phone inquiry $47.97

For the purpose of this analysis, it has been assumed that the average electricity cost is 20 c/kWh. The Yr 6 report used 13.7c/kWh: 20/13.7 = 1.46.

24.14.1.3 GHG emissions

Based on 2005 generation and GHG emission data (MOE 2007a & 2007b) the emissions factors for thermal electricity using gas and coal are 0.39 kg CO_2/kWh and 0.91 kg CO_2/kWh respectively. Although the proportions of gas and coal generation shift year-by-year, for the purposes of this analysis it has been assumed that 60% of thermal generation is coal and 30% is natural gas, giving a combined emission factor of 0.51 kg CO_2/kWh..

24.14.1.4 Scrap

Older, low pressure, copper hot water cylinders can have significant scrap values. The scrap value of a copper hot water cylinder is about $60 for a 30 gallon (135 litre) tank, and $80 for a 40 gallon (180 litre) tank, or slightly more for the copper insert alone[46].

24.15 Improving cylinder electricity efficiency

The majority of New Zealand water heaters are electric low-pressure storage systems (see Section 24.9.2). Note that installing cylinder wraps on gas storage cylinders is potentially dangerous, and would not be as effective as for electric systems because the flue and pilot light (if used) would not be reduced.

24.15.1 Opportunities to improve cylinder efficiency

Of the electric cylinders, by far the most common cylinder sizes are 135 litre (30 gallon) and 180 litre (40 gallon) which are each 43% of the total electric storage cylinders (see Table 154). The cost of cylinder wraps appears to be the same for 135 litre and 180 litre cylinders. Potential energy savings from improvements in efficiency are likely to be higher for the 180 litre systems, so targeting these may be slightly more cost-effective.

Most purpose-installed night-rate electric hot water systems are already well insulated, so it is likely that adding cylinder wraps would provide only marginal benefits.

HEEP has found that very few hot water systems of any age or grade have cylinder wraps (only 4%), or pipe insulation close to the cylinder. Pipe insulation is likely to be equally cost-effective on all sizes and types of hot water systems, including gas systems. The impact of the EECA 'Energy Wise Home' grants which promote the use of cylinder wraps was not widely visible during the period the HEEP monitoring was undertaken.

Cylinder wraps are most cost-effective on the older, poorer insulated, C or D grade cylinders, and these should probably be the targeted cylinder types. The HEEP information could be used to develop a decision support tool for identifying which houses have C or D grade cylinders before time and money is invested in visiting a house.

About 40% of the HEEP electric hot-water cylinders are C or D grade (Table 172). To implement widespread cylinder wrap installation or cylinder replacement campaigns, information is needed on what type of houses these poorly performing cylinders are likely to be in. This would allow areas to be targeted that may have a high prevalence of C or D grade cylinders. The type of information is available from the Census and other public sources and includes:

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[46] Phone enquiry to Wellington Scrap Metals, 23 July 2007

1) age of house
2) size of house
3) size, age and income of household.

Once households have been targeted, they need to be vetted at both the inquiry and visit stage to avoid retrofitting the lower loss, better insulated A or B grade cylinders. At that point information that is specific to the individual house and hot water system can be used, such as:

1) age and size of hot water cylinder
2) pressure (mains, low, header tank)
3) cylinder information such as brand, model, insulation type, etc.

Hot-water cylinders are normally installed when a house is built and replaced either if they fail, or as part of renovation. The age and grade data from HEEP, summarised in Table 172, bears this out.

House Age **Cylinder Grade**	**pre-1910**	**1910s & 20s**	**1930s**	**1940s**	**1950s**	**1960s**	**1970s**	**1980s**	**1990s**	**2000s**	**NA**	**TOTALS**
A or B	12	8	9	10	21	29	20	31	40	8	19	**207**
C or D	2	15	9	5	34	25	40	11	2	-	14	**157**
Uninsulated	-	-	-	-	-	-	-	-	1	-	-	**1**
NA	2	1	-	-	3	3	3	-	3	-	3	**18**
TOTAL	**16**	**24**	**18**	**15**	**58**	**57**	**63**	**42**	**46**	**8**	**36**	**383**
% C or D	13%	63%	50%	33%	59%	44%	63%	26%	4%	0%	39%	41%

Table 172: Count of cylinder grade by house decade of construction

All houses from the 1990s have A or B grade systems, as do most houses from the 1980s. This is expected as B grade or better cylinders were in use after 1993 and A grade have been required since 2003 (see Table 141 for specifications). Houses from the 1950s to the 1970s have a mix of all cylinder grades, but older houses are likely to have mainly A or B grade systems as the original cylinder will have been replaced.

Table 172 suggests the richest mine of C or D grade electric cylinders is in the group of 1950s to 1970s houses. Most of the C or D grade cylinders in the 1960s and 1970s houses are the original cylinder, but only about half of those in the 1950s houses are, and the oldest of these are likely to be near the end of their life. The cylinders in the 1970s houses are probably the best targets for cylinder wraps, as the majority are C or D grade and they are likely to have a number of years of operation left. The cylinders in the 1960s houses are on average about 10 years older, and so are more likely to need replacement soon than those in the 1970s houses. Any original cylinders in 1950s houses are probably close to failure. For older houses, (1940s and earlier) almost none of the original cylinders are still in place (many of these houses pre-date the widespread use of electric water heaters), and most of the C or D grade cylinders are likely to have been first or even second replacements.

Figure 148 showed that there are major variations in cylinder grades between regions and that there are also variations within each region. The reasons for this are unknown, but could be caused by water conditions degrading cylinders faster in some regions, economic or demographic factors.

Once regions or areas are targeted, the installer must decide whether the cylinder needs a cylinder wrap. HEEP information can give guidance here. The age of the cylinder (if known) is the best guide, as D grade cylinders are likely to be pre-1980, and most 1980s and later cylinders are B grade. Many modern cylinders have a label with the date of manufacture, and the make and model number, which can often be used to determine the cylinder grade.

Older cylinders, unfortunately, often have no age mark or useful label and other information must be used. The insulation type is a good indicator, as A or B grade cylinders are usually insulated with polyurethane or polystyrene foam, and C or D grade cylinders generally have cloth or fibre insulation. Very old cylinders look obviously old, though this is only a help for the oldest ones – for example with cylinders of intermediate age it can be impossible to tell a 1970s C or D grade from a 1980s A or B grade cylinder. Any system with a thermostat that reads degrees Fahrenheit is almost certainly D grade. Very few cylinders larger than 180 litres are C or D grade.

HEEP has a large body of practical information for identifying the grade of cylinders from visual inspection. HEEP information can be used to help optimise the upgrading strategy, and increase both the uptake and eligibility rate of marketing and promotion, and the energy savings per wrap installed.

24.15.2 Cost-benefit analysis

Of the hot water systems surveyed, very few of any age or grade had cylinder wraps (only 4%), or pipe lagging. Pipe lagging is likely to be equally cost effective on different sizes and types of hot water systems, including gas systems. Pipe lagging was used on some pipes in roof spaces for some Christchurch houses, possibly to prevent freezing of pipes in winter.

Grade	Savings kWh/yr	Savings/yr Electricity 20.0 c/kWh	Savings/yr Carbon $25/tonne	Simple Return	Simple payback $150 per wrap (yr)
A or B	36	$7.30	$0.13	5%	20.2
C or D	219	$43.80	$0.76	30%	3.4

Table 173: Cylinder wrap cost benefit by cylinder grade

Table 173 provides an analysis of the annual savings from installing a cylinder wrap on an 180 litre electric storage cylinder of different grades based on the measured results reported in Table 142. At $150 installed, the simple payback is just over three years for the addition of a wrap to a C or D grade cylinder. It is interesting to note the small impact of even a $25 per tonne carbon charge ($6.80 per tonne CO_2 assuming all of the electricity is from thermal generation) – only about 2% of the savings. Even increasing the carbon charge to $100 per tonne ($27 per tonne CO_2) makes this only 7% of the savings, suggesting the carbon charge is of limited value as an economic driver. A lower cost wrap (either installed by house occupants or as part of a larger energy efficiency project) would result in a faster payback.

Table 142 suggests that for a 135 litre D grade (measured loss 2.8 kWh/day) cylinder, replacement with either a new A grade cylinder (measured loss 2.1 kWh/day – savings 0.7 kWh/day) or the addition of a cylinder wrap (measured loss 1.8 kWh/day – savings 1 kWh/day) would give comparable energy savings and GHG reductions, although the D-grade will still have a finite lifetime.

Table 174 is based on a comparison against an existing D-grade 180 litre electric storage cylinder with electricity at 20 c/kWh and gas at 11 c/kWh. The gas alternatives are assumed to use 20% more hot water than the electric options. The heat pump system is assumed to have a COP of 3, conventional gas efficiency of 80% and condensing gas efficiency of 95%. The solar system is assumed to provide 50% of household hot water. The prices for each of the measures were obtained from Negawatt Resources, Rinnai NZ, Plumbing World, PlaceMakers or Mitre10, during April-August 2007. Energy prices are based on MOE (2007a).

Measure	Installation ($)	Installed Cost ($)	Savings ($/yr)	Simple Payback (yr)
Electric				
Self installed wrap & pipe insulation	$0	$90	$40	2
Cylinder wrap & pipe insulation	$60	$150	$40	3
New A grade (180 l mains)	$500	$1,400	$40	38
Heat pump DHW (310 l)	$1,000	$6,250	$420	15
Solar (inc. new electric cylinder)	$3,000	$7,000	$320	22
Gas (use 20% more hot water)				
New gas cylinder (152 litre)	$1,000	$2,200	$240	9
New Gas instant (24 litre)	$1,000	$2,400	$400	6
Gas condensing continuous flow (24 litre)	$1,000	$3,000	$460	7

Table 174: Some alternative measures for D grade 180 litre retrofit

Table 174 shows that unless the cylinder needs to be replaced (e.g. due to failure, house modifications, etc) then cylinder wrapping is by far the most cost-effective measure, with natural gas options following. Replacement of an old inefficient electric cylinder with a modern, higher efficiency electric cylinder cannot be justified simply on energy efficiency cost benefits, unless the upfront cost is reduced.

Buyback schemes have been run successfully overseas for everything from petrol-powered lawn mowers to halogen torchiere uplights. A buyback or rebate scheme for old hot water cylinders might be cost-effective, and might encourage early replacement with high efficiency ‘A’ grade systems.

24.15.3 Potential savings from installing cylinder wraps

Table 142 showed the wrapped cylinders from HEEP have standing losses of 1.0 kWh/day less than the C or D grade unwrapped cylinders for 135 litre systems, and 0.6 kWh per day less for the 180 litre cylinders. If these are typical of the energy savings for wrapping cylinders, then the ongoing savings from installing wraps on the approximately 240,000 unwrapped 135 litre and 160,000 180 litre systems would be 122 GWh per year, with a retail electricity cost of about $24 million per year (20 c/kWh).

There are also additional potential savings for wrapping both larger and smaller cylinders (numbering about 50,000 cylinders), although HEEP estimates of the achieved savings from wraps are not available due to the insufficient number of monitored systems.

Cylinder wraps and pipe insulation could also give energy savings for A or B grade systems, although the savings would be smaller. Assuming a conservative 0.3 kWh/day saving, the potential ongoing savings for the approximately 600,000 A or B grade systems would be 66 GWh per year, with a retail electricity cost of about $13 million per year.

24.16 Cylinder wraps in reality

As part of the HEEP data quality assurance, photographs were taken of major household appliances. The examples in Figure 168 illustrate the various types of electric hot water cylinder wrap installation. The quality of the installations varies widely, with some wraps so poorly installed as to be ineffective.

Figure 168: Examples of electric hot water cylinder wraps

It is not known whether these wraps were installed by the occupants, by others or under any external funding programme, such as those supported by EECA's Residential Grants programmes.

It is critical that cylinder wraps are installed properly to ensure that the maximum savings are achieved, and that these benefits are not rendered ineffective by any later actions of the occupants or tradespeople.

24.17 Reducing hot water energy use

"Before project-based activities take place a company needs to develop a methodology to verify and quantify any emissions reductions to evaluate the environmental and investment opportunities of the projects" (Kessels 2002)

HEEP results can be used to provide useful data, and ultimately a tool, to assist energy companies to assess the GHG benefits of energy efficiency activities.

There are a number of ways to reduce hot water energy consumption, and hence GHG emissions. Table 175 provides examples of achieving this through reducing losses, reducing hot water use and reducing the GHG emissions factors.

Reducing energy losses	Pipe insulation Cylinder wrap Adjusting thermostats to lowest possible storage temperature Accurate thermostats Switching off or turning down cylinders when house vacant Replacing with new cylinders
Reducing hot water use	Fixing leaks Repairing defective pressure-reducing valves Installing low-flow shower heads Educating occupants about water use, e.g. clothes washing, baths & showers
Reduce GHG energy factor	Heat recovery or cold water preheating Install solar water heater or heat pump Use solid fuel 'wetback' supplementary water heating Convert from electricity to gas

Table 175: Methods to reduce hot water emissions

HEEP results permit the cost-effectiveness and takeback of some of these measures to be examined. Unanswered questions include whether the use of mains pressure cylinders encourages higher hot water use, and whether low-flow shower heads reduce hot water use.

Many households turn the thermostat up high so that they have sufficient hot water. Adjusting thermostats to lower settings to reduce standing losses, which is a common procedure in energy audits, may lead to inadequate water delivery or showers. Consequently, many of these thermostats may be turned up again (Tustin, 1991).

It should be noted that a 135 litre cylinder storing water at 75°C holds the same energy as a 180 litre cylinder with water stored at 55°C, but the higher temperature is clearly unsafe for all users. There are thus very important health benefits if the cylinder temperature can be reduced by increasing cylinder size at the same time as improving the energy efficiency.

24.18 Conclusions

Over the past century readily available hot water has changed from being a rich person's luxury to a basic expectation. The availability of piped water, suitable water heating storage containers and energy supplies (notably electricity) all combined to make it possible for any household to expect hot water to be readily available. Whether the hot water systems found in most New Zealand homes are appropriate for the next century is not as clear.

HEEP has found that today's homes often have inadequate supplies of hot water, sometimes delivered at dangerously high temperatures and often at temperatures that are not those expected from the indications of the controls.

Hot water use varies greatly from person to person, and consequently from household to household. Most households' demands can be met with a storage system. In common low pressure electric storage cylinders, an average of 45 litres per person of hot water storage capacity can be considered a reasonable minimum, although if the recovery time is long there will be times when this is insufficient. As the number of people in a house changes more often than the hot water storage, storage is often insufficient.

Low pressure systems can last many years providing the water quality in the area is satisfactory, but the shower flow rates are likely to be below those found in 'low flow' shower heads and without the careful spray design.

High pressure storage systems are likely to have shorter storage tank lifetimes and the higher water flow rates require the use of 'low flow' shower heads to limit both the use of water and water heating energy. Of particular concern is the direct replacement of low pressure system with high pressure systems without any change to the fittings – shower and taps.

New Zealand has a high proportion of electric water heating, although gas has recently become more popular, especially in households with greater hot water needs. Solid fuels (notably wood) are also of significance as hot water fuels, especially during winter in the colder parts of the country. The move away from solid fuel heating to lower local air pollution systems (e.g. space heating heat-pumps) will increase the hot water heating load on the central energy supply systems – not ably increasing the winter electricity peak.

There is potential to improve the energy efficiency of hot water systems by means of:

- use of water efficient shower heads
- insulation of hot water pipes and storage tanks
- accurate thermostatic control of water temperature

- lowest possible water storage temperatures
- switching off of systems when house unoccupied for long periods of time
- minimising water leaks
- greater adoption of low GHG water heating fuels e.g. solar water heating, wood, etc.

25. ENERGY USE OF HEEP HOUSES COMPARED TO ALF3

This section explains a comparison study between household energy use estimated from HEEP monitoring, and household energy use calculated from a modelling program (ALF3).

HEEP monitored energy use in occupied houses, and produced estimates of annual heating energy. The Annual Loss Factor, 3rd edition (ALF3) (Stoecklein and Bassett, 2000) is a modelling program which estimates the annual heating energy required for a residential building based on the house's physical location and construction, and a selected heating schedule.

ALF3 does not consider the efficiency and responsiveness of heaters. It assumes that the heating level is instantly achieved with whatever heating appliances are installed. If the evening only heating schedule is used it does not, therefore, take account of any energy needed before 5.00 p.m.

All houses in the HEEP database (including non-random houses) that were able to be modelled in ALF3 were modelled – a total of 375 houses. Some houses in the HEEP pilot study were lacking enough information to model, principally in Wanganui and Wellington.

Modelling of the houses in ALF3 was undertaken by Ruwan Fernando, a BBSc student at the School of Architecture, Victoria University of Wellington.

25.1 Modelling

All houses that had sufficient information to permit the creation of an ALF3 model were modelled, although some houses had more data available than others. In some cases, elements had to be estimated using other information available, e.g. window sizes taken from photos rather than house plans.

Three of the more complex houses were modelled as two separate ALF3 models. Two of these houses have sleep-outs, while the other had an extensive addition in a different construction to the original house.

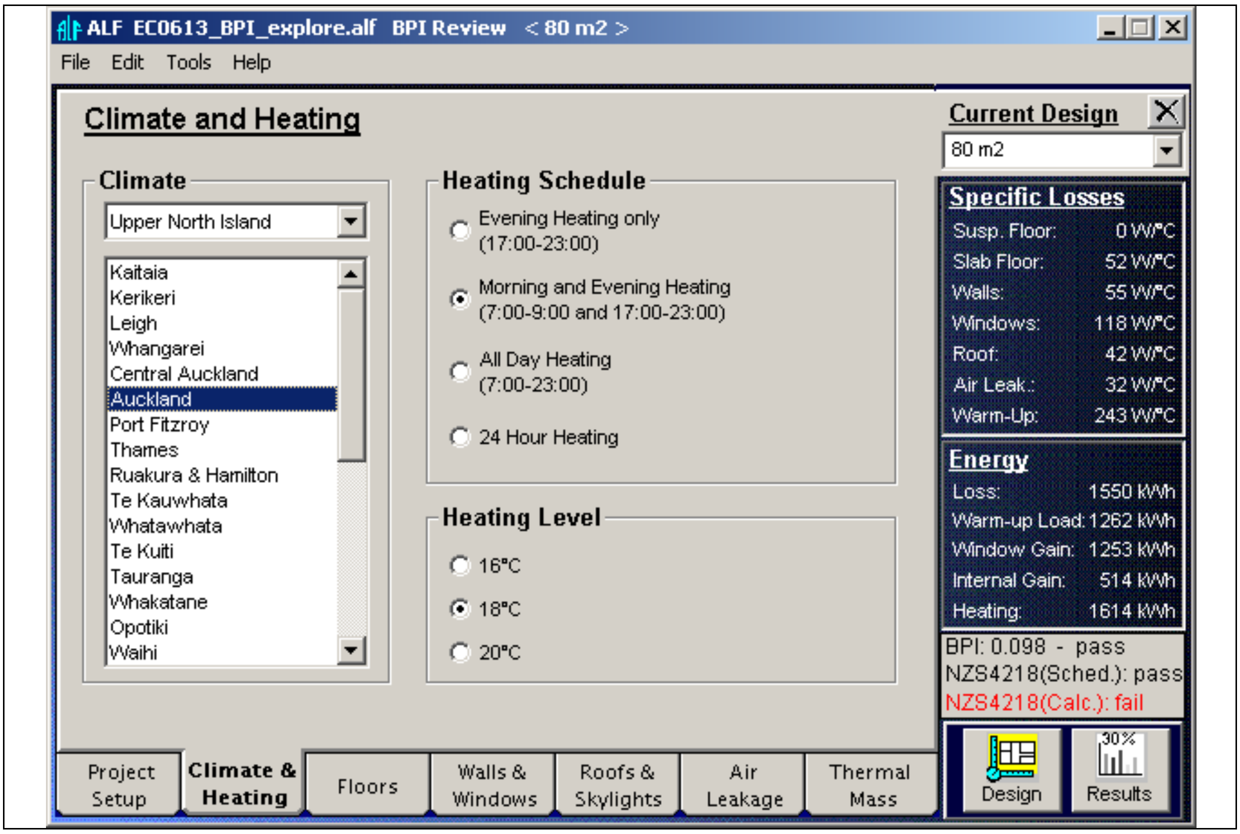
25.2 Selection criteria

Houses with electricity, natural gas and LPG heating were included, from Kaikohe to Invercargill. No limits were placed on occupants, locations or any other house characteristics. During modelling, some houses some were found to be unsuitable due to missing data on physical characteristics such as window dimensions, orientation, insulation details etc. Houses that had no heating appliances (all in Northland or Auckland) were also considered unsuitable for the comparison. Because of the higher population of solid fuel burners in rural and southern regions, fewer houses were available in these areas than hoped.

25.3 ALF3 heating energy estimates

Each house was entered into ALF3 using the physical dimensions and occupant data held in the HEEP databases. The most appropriate heating schedule and set point were entered.

Figure 169 provides an illustration of an ALF3 input screen. The left side is used for data input – in this case the house location, the heating schedule and the heating temperature level. The right side provides a summary of the specific losses for each component of the building, the energy balance, and whether the house complies with one of the three possible compliance routes for NZBC Clause H1: Energy Efficiency.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Climate and Heating

Climate

Upper North Island

Kaitaia
Kerikeri
Leigh
Whangarei
Central Auckland
Auckland
Port Fitzroy
Thames
Ruakura & Hamilton
Te Kauwhata
Whatawhata
Te Kuiti
Tauranga
Whakatane
Opotiki
Waihi

Heating Schedule

○ Evening Heating only (17:00-23:00)
● Morning and Evening Heating (7:00-9:00 and 17:00-23:00)
○ All Day Heating (7:00-23:00)
○ 24 Hour Heating

Heating Level

○ 16°C
● 18°C
○ 20°C

Current Design

80 m2

Specific Losses

Susp. Floor:	0 W/°C
Slab Floor:	52 W/°C
Walls:	55 W/°C
Windows:	118 W/°C
Roof:	42 W/°C
Air Leak.:	32 W/°C
Warm-Up:	243 W/°C

Energy

Loss:	1550 kWh
Warm-up Load:	1262 kWh
Window Gain:	1253 kWh
Internal Gain:	514 kWh
Heating:	1614 kWh

BPI: 0.098 - pass
NZS4218(Sched.): pass
NZS4218(Calc.): fail

Figure 169: ALF3 screen image

Figure 169 illustrates how ALF3 provides annual energy balances (in kWh) for the total house on the right side of the input screen:

- energy **Loss** through the building envelope
- **Warm-up Load** after the house has been allowed to cool
- **Window Gain** from utilisable solar energy
- **Internal Gain** from occupants and appliances
- **Heating** energy required to maintain the various heating levels.

The ALF3 reported **heating** energy is the difference between the utilisable energy gains (solar, occupants and appliances), the energy losses (through roof, wall, floor, windows and due to infiltration) and includes the warm-up energy.

This section compares the calculated ALF3 heating energy use with the estimated HEEP heating energy use. However, the assumptions used by ALF3 to calculate the energy loss, warm-up load and internal gains will affect the validity of the calculation of the total house heating energy use. The two most important assumptions concern the length of heating and the maintained indoor temperatures.

25.3.1 Heating months

It was decided that the measured heating season was more appropriate to use in this analysis (see sections 7.4 to 7.6). Based on these heating schedules, the ALF3 climate file was updated to better reflect the monitored houses. Table 176 compares the HEEP heating season and standard ALF3 heating season.

Location	Length of Heating Season

	HEEP	ALF3
Kaikohe	5	1
Whangarei	6	1
Auckland	6	3
Parawai	5	3
Tauranga	5	3
Hamilton	7	4
Arapuni	8	5
Rotorua	7	5
Mangapapa	7	3
Rangatira	8	5
Wairoa	7	3
Tamatea North	6	3
Foxton Beach	6	5
Waikanae	6	5
Wellington	6	5
Wai-iti	7	5
Seddon	8	5
Christchurch	7	5
Oamaru	9	6
Dunedin	8	6
Invercargill	8	8

Table 176: Length of Heating season

The HEEP values are averages for the area. Within each area, the heating seasons do vary significantly from house to house, especially in the warmer areas with the lower average heating months.

Not all HEEP locations have their own ALF3 climate file, so these have been assigned to the closest ALF3 climate. The following ALF3 areas include more than one HEEP location:

- Auckland includes: Orewa, Auckland City, Manukau, North Shore, Waitakere and Awhitu
- Tauranga includes Minden
- Whangarei is the suburbs of Kamo West and Sherwood Rise
- Rotorua includes Ngakuru and the suburb Western Heights.

Not all heating months could be determined due to missing data.

25.3.2 Heating schedules

Heating times during the day and night were determined by looking at daily temperature and energy profiles over the winter months. Where houses are heated by solid fuel or LPG, separate profiles for each of these fuels were also examined. The energy use shown in Figure 170 and Figure 171 is the total electricity and gas use, with the energy for heating the hot water removed (i.e. non-hot water energy use).

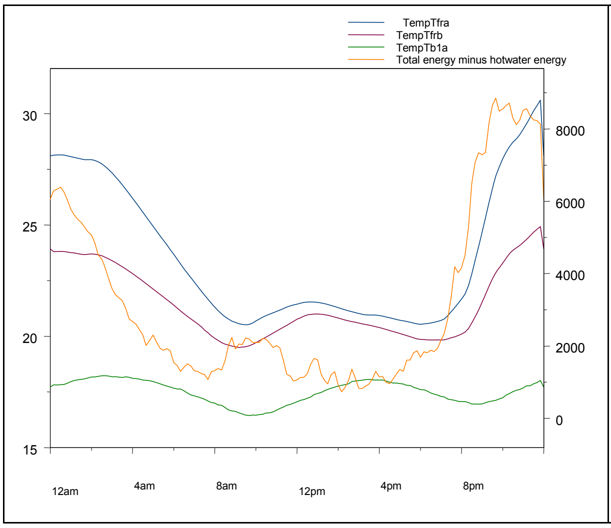

Figure 170:Daily profile of inside temperatures and energy use – weekend

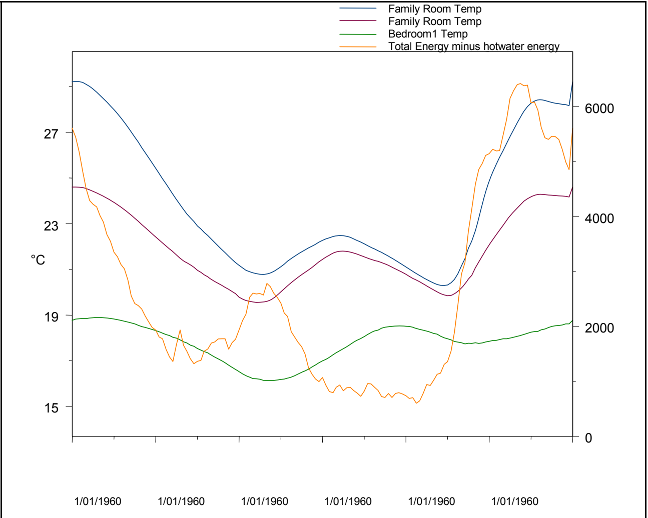

Figure 171: Daily profile of inside temperatures and energy use – weekday

The hours of heating were recorded and the total number of hours heated calculated for the average day. Then the best matched ALF3 heating schedule (Table 177) was chosen, mainly based on the number of hours heated rather than the time of day.

Hours of Heating	Schedule Name	No. of Hours
5–11pm	Evening only	6
7–9am and 5–11pm	Morning and evening	8
7am–11pm	All day	16
24 hr	24 hr	24

Table 177: ALF3 heating schedules

Not all houses could have their heating schedules determined due to missing data. If there was any doubt in determining the heating schedule, they were not included for this analysis. Often, the heating schedules of houses were found to be slightly shorter than the options given in Table 177. If morning heating was used, then one hour of heating would be more common than two, while evening heating would often be less than six hours, especially in warmer areas of the country.

25.4 Heating temperature

ALF3 models the heating period at one of four pre-set schedules and the temperature at one of three pre-set levels (see Figure 169), e.g. between 17:00 and 23:00 the temperature is maintained at a constant 18°C. In reality, New Zealand living rooms are not kept at a fixed temperature. The heating level for use with ALF3 was determined by calculating the mean temperature of the HEEP house during the heating period.

To examine the importance of assuming a constant (mean) temperature rather than a dynamic (changing) temperature, a house was modelled using SUNREL[47]. Two heating schedules were tested – one with dynamic temperatures (a house with a warm-up and cool-down period) and one with a set heating level (an ALF3 model), on both a high mass and lightweight construction house. The heating energy use (June to August inclusive) for the two house constructions were within 4% of each other, supporting the use of this simplification.

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[47] SUNREL website: www.nrel.gov/buildings/highperformance/sunrel/

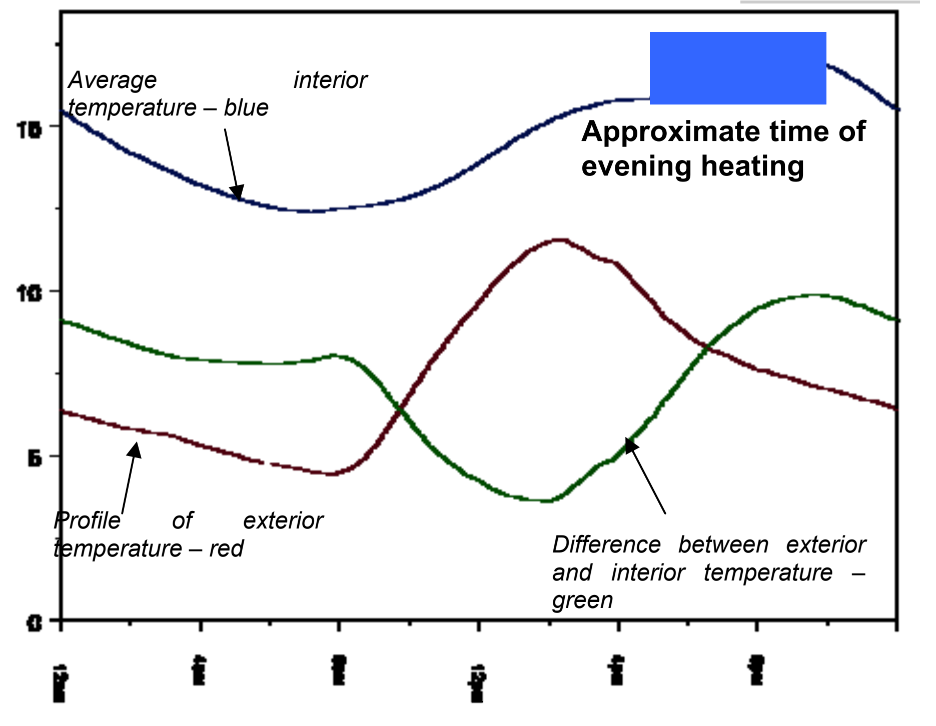

Figure 172: Winter temperature profiles for Christchurch HEEP houses

The main heating period was during the evening for the majority of the HEEP houses. The start of heating can be determined from a daily average temperature profile. The time at which a sharp rise in temperature is coupled with a falling exterior temperature is defined as the start of heating. This heating period is highlighted in Figure 172. An average evening start and finish time was calculated for each location, and then the mean temperature calculated for each house during this period.

The maximum temperature is reached some time into the heat period, and at this point the occupants reduce, but do not stop, heating. The end of heating was determined by finding the point in the daily average temperature profile at which the difference between the outside and inside temperature decreases.

Location	Start	Finish	Hours
Auckland	6:00	10:00	4 hr
Hamilton	5:10	9:20	4 hr10 m
Tauranga	5:30	9:30	4 hr
Wellington	5:00	10:10	5 hr10 m
Christchurch	5:20	9:40	4 hr 20 m
Dunedin	5:00	10:00	5 hr
Invercargill	4:00	10:00	6 hr
Clusters	4:10	9:30	5hr 20 m
ALF3 evening heating	5:00	11:00	6 hr

Table 178: Mean heating times on winter evenings

Evening heating times for the selected locations are given in Table 178, and range from 2 hours to 6 hours. One of the standard ALF3 heating regimes is for evening heating of 6 hours – 17:00 to 23:00 (see Figure 169).

Once the evening heating times were established, the mean temperatures could be calculated from the monitored family room temperatures for the months of June, July and August.

Heating levels range from 9.6°C to 25.3°C during the periods mentioned in Table 178 for the entire HEEP sample, and from 12.9°C to 25.3°C in the selected sub-sample. The range of heating levels can be seen in Figure 173 for the entire HEEP sample.

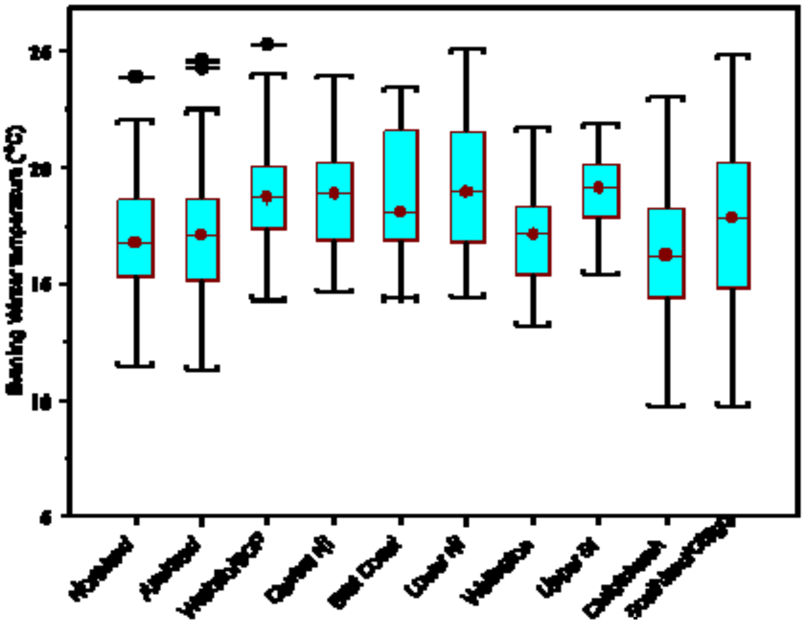

Figure 173: HEEP sample mean average winter evening temperatures

There are three temperature options in ALF3 as seen in Figure 169 – 16°C, 18°C and 20°C. The ALF3 heating levels used to estimate the heating energy use for a given house are determined by calculating the mean temperature as described above, and then selecting the ALF3 heating temperature based on the ranges shown in Table 179.

ALF3 heating temperature (°C)	**16°C**	**18°C**	**20°C**
Calculated average temperature	< 16 – 17°C	17.1 – 19°C	Above 19.1°C

Table 179: Average heating temperatures in selected houses

In cases where the average evening temperatures differ from the options available in ALF3, then extrapolation or interpolation as set out in the ALF3 manual, Section 5.3 can be used. Albrecht Stoecklein (an author of ALF3) suggests that extrapolation can only be reliably carried out from 14°C to 22°C. The ALF3 model becomes very sensitive to small changes in temperature in a warm climate when the heating temperature is set below 16°C, so it is not recommended to use the model in this situation (ALF3 Manual, Section 5.3). Approximately 75% of the houses in the HEEP database have a mean winter evening living room temperature of between 14°C and 22°C.

The interpolation or extrapolation method as suggested in the ALF Manual, Section 5.3 was not used for this analysis. A degree hour correlation was developed (Section 25.7.1) which also takes into account the different heating hours used in the HEEP houses compared to the ALF heating hours.

The range of temperatures in the selected sub-sample can be seen in Table 179 and Figure 173. Of the 31 houses in the <16–17°C range, 17 houses were below 16°C and in the upper range 16 houses were above 20°C. These are houses that are outside of the range of options in ALF3.

Figure 174 and Figure 175 provide frequency information on the living room winter evening temperatures for the selected sample.

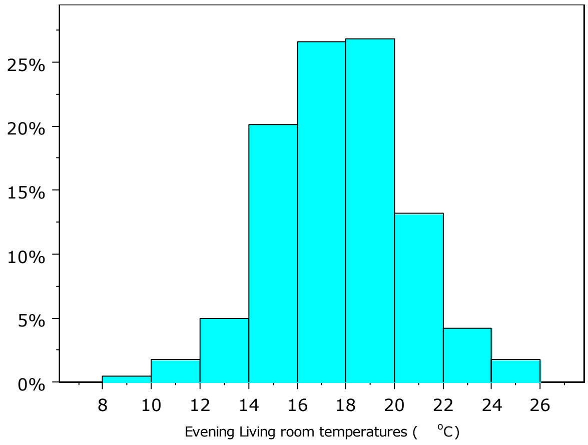

Figure 174: Histogram of living room evening temperatures in selected sample

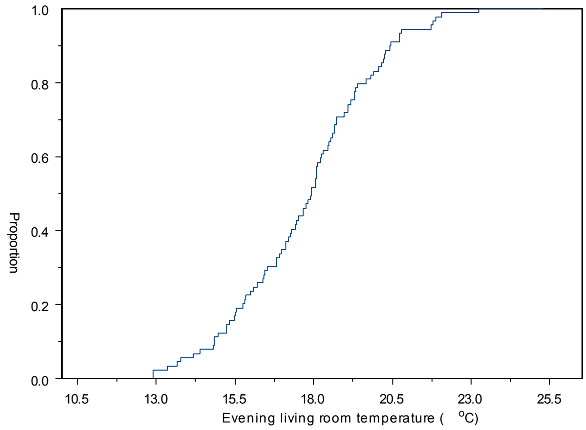

Figure 175: Cumulative frequency of living room temperatures in selected sample

25.5 Modelling issues

It should be noted that houses that have no heaters, or where the owners claimed not to heat, are not included in the sample selection.

25.5.1 Missing information from HEEP material

The ALF3 model requires information in greater detail on house construction and use in some areas than available in the HEEP database. Details that are often lacking include the spacing between studs in a wall, the insulation thickness inside that wall and the materials and construction method. These issues will often be a problem when establishing component R-values in order to model existing houses with little or no information on their construction. The areas where assumptions have been made are explained below.

Simplification of construction types for walls and roof

Modelling in ALF3 required simplification of construction types for walls and roof as often many details of construction were unknown. A table of wall and roof types was developed by Roman Jaques and Ian Cox-Smith (Jaques et al, 2003), and is reproduced as Table 180.

Insulation R-value (m²°C/W)	WALLS			ROOF	
	Wall EIFS	Timber Framed			
		Weatherboard	Sheet cladding	Battens	Dwangs
1.3	1.5				
1.8	2.0	2.0	1.7	2.1	1.7
2.2	2.4	2.1	1.9	2.5	1.9
2.6	2.8	2.3	2.1	2.8	2.1
3.0		2.5	2.2	3.2	2.3
3.4				3.6	2.5
3.6				3.8	2.6
4.0				4.2	2.7
5.0				5.2	

Table 180: Wall and roof construction

Components that have no added insulation are not covered in Table 180. For these components the R-values in Table 181 were developed based on the *BRANZ Insulation Guide* (Van der Werff, 1995).

(m²°C/W)	Weatherboard	Sheet cladding	Brick veneer	Roof
Construction R-value	0.6	0.4	0.5	0.4

Table 181: Construction R-value with no insulation

It is believed that the tables above can result in R-values that are too generous for older houses and not generous enough for new houses, but in the absence of other information this is the best available approach.

Insulation thickness

The thickness of insulation in walls was particularly hard to assess, as it is hidden by the wall cladding. Wall insulation thickness was taken to be between 90 and 95 mm, unless records reported a 150 mm wide wall where the insulation would be thicker.

The depth of ceiling insulation was recorded for the HEEP houses where the ceiling space was accessible. When the ceiling insulation R-value was estimated, the age of the house was considered as changing regulations have seen a required increase in the thickness of insulation. It is also expected that there will be some deterioration of thermal performance over time.

Information on the insulation is not complete, with 17 houses missing information on floor insulation, 22 houses on ceiling insulation and 20 houses wall insulation.

Slab insulation

Slab insulation was unknown in most cases, so unless the owner knew about the construction of the house it was assumed that no insulation was under the slab. Two house owners knew their house to have under-slab insulation.

Dwangs or battens in the roof

Information on the house having battens or dwangs in the roof is not recorded in the HEEP databases. For the purposes of this study, houses from 1980 onwards have been modelled with battens and houses before 1980 with dwangs.

Sheltered/exposed perimeter wall

ALF3 requires information on the shelter of the perimeter wall – whether it is exposed or protected from the wind. The HEEP survey does not record the degree of shelter at the perimeter wall. As each house has an extensive photographic record, the shelter of the perimeter wall could be determined. This was used for the 47 houses with suspended floors.

Thermal breaks in windows

Dimensions, single or double glazing and window covering were recorded at the time of installation for windows, but there was no information recorded on presence or absence of thermal breaks in aluminium window frames. Thermal breaks in New Zealand are considered to be rare due to the price compared to standard frames. For all houses with aluminium windows the ‘no thermal break aluminium frame’ was selected.

Varying stud height/sloping ceiling

When the ceiling was of varying height, an average stud height was calculated. This was then used as the ceiling and wall height when modelling in ALF3 (used for five houses).

25.5.2 ALF3 modelling issues

In addition to assumptions of the physical construction, it was also necessary to deal with other design issues.

Common walls between flats

Thirteen of the selected dwellings were apartments with one or more common wall(s). Common walls can not be treated as external walls, as often the adjacent space (the next-door neighbour) is heated or at least protected from the elements. If the neighbouring flat is heated to the same temperature there would be no heat transfer, but this cannot be assumed at all times. As a coarse adjustment for the higher thermal resistance between heated and unheated zones, the common wall R-value was increased by a factor of 0.5, as suggested in Section 5.4.1.1 of the ALF3 manual.

Conservatories

Conservatories can greatly affect the thermal performance of a building. There are two types:

- the conservatory is separated from the rest of the house by a door, wall or window.
- the conservatory has a direct opening to the rest of the house.

The ALF3 Manual, Section 5.5.2 suggests suitable methods:

- When the conservatory is open to the rest of the house, it is treated as a large window. The insulation value of the components separating the conservatory from the house is increased by the conservatory glass R-value. This approach generally underestimates the solar gains, but also underestimates the losses.
- Where the conservatory is open to the house, it is treated as a large window. Solar gains and window losses are calculated as for a normal window.
-

There were five houses with conservatories that can be separated from the rest of the house, and two conservatories which are open to the house.

Frosted glass

The effect of frosted glass or net curtains on solar shading differs for the many types. BRANZ Senior Scientist, John Burgess, suggested 20% as a realistic average.

Height of sub-floor perimeter wall

The height of sub-floor perimeter walls often vary, especially on a sloped site. The HEEP site inspection recorded either an average height or a range of heights. If a range was given, the average was taken, and the house photos were used to assist the process. The height of the perimeter wall was used for the 47 houses with suspended timber floors.

Floor covering R-value

In most houses floor coverings vary between rooms, with low R-value vinyl or tiles mainly in service areas and higher R-value carpet in living areas. The percentage of the floor covered in carpet was calculated and the carpet R-value of 0.4 multiplied to give the house average, e.g. if 50% of the house was carpeted, the overall floor R-value increased by 0.2.

Wind exposure

ALF3 has four classes for wind exposure – sheltered, medium sheltered, medium exposed and exposed, as shown in Figure 176, which was also used in the HEEP survey. If the occupant-reported wind exposure was thought to be too high, it was checked against the ALF3 wind exposure map (ALF3 Manual, Section 1.2) and modified to a lower level.

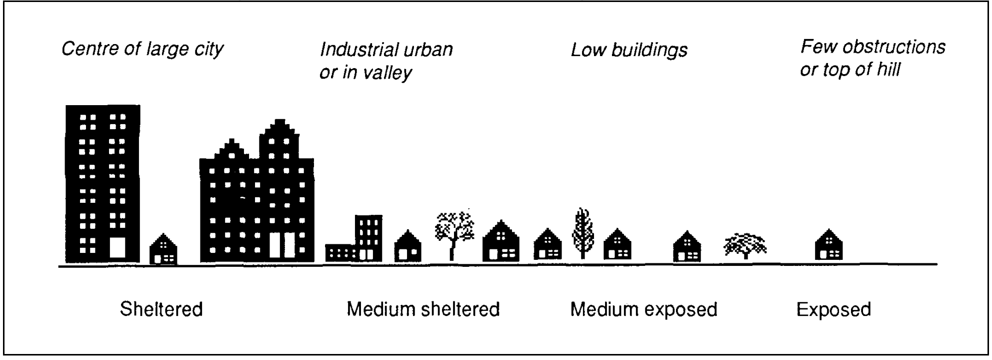

Figure 176: Wind exposure classes

House air leakage

The survey asks for an assessment of the air leakage of the house. The ALF3 Manual gives a guide for calculating air leakage based on the design and age of the house (Table 182). As some occupants were thought to be too extreme in their assessment, the air leakage was based on the occupant opinion, house plan and photographic evidence.

	Base air leakage (air change per hour)	Typical example
Airtight	0.25	simple, small rectangular, airtight joinery, all windows with gaskets
Average	0.50	larger than 120 m²
Leaky	0.75	complex shape, some match lining materials, generally over 200 m²
Draughty	1.00	pre-1960, match lining, match flooring, often high stud

Table 182: Air leakage rates

Climate and location

Four of the smaller localities – Waikanae, Foxton Beach, Kaikohe and Minden do not have climate files in ALF3. For these locations, a neighbouring town with a climate file was used. The four locations affected and the ALF3 climates are given in Table 183.

HEEP location	ALF3 climate location
Kaikohe	***Kerikeri***
Whangarei	Whangarei
Auckland	Auckland
Hamilton	Ruakura and Hamilton
Minden	***Tauranga***
Tauranga	Tauranga
Foxton Beach	***Levin***
Waikanae	***Paraparaumu***
Wellington	Wellington
Christchurch	Christchurch
Oamaru	Oamaru
Dunedin	Dunedin
Invercargill	Invercargill

Table 183: Climate locations

With the development from ALF2 to ALF3, interpolations functions were developed to allow any New Zealand location to be modelled if the monthly average temperatures and monthly number of sunshine hours are known (see ALF3 Manual, Section 6.1). This was not considered necessary for this study, as the climate file mainly affects the length of the heating season, which was manually changed in the climate file to match the occupants' heating patterns.

For the Auckland houses, there was the option of the Auckland central or the Auckland region climate file. The Auckland central file was significantly warmer, with heating only for one month of the year. This was considered unsuitable, as the Auckland HEEP houses heat on average for three months. The Auckland region climate was considered more realistic in terms of temperatures and was thus used in the Auckland ALF3 models.

House heating zones

Earlier work found the majority of HEEP houses heat only a portion of their homes – generally the living room (Isaacs et al, 2003). For the selected houses, only 28% heat the bedrooms and living room on a regular basis, with only 5% regularly heating the whole house. In the total HEEP sample, 46% of houses heat their bedrooms and living rooms on a regular basis.

ALF3 assumes the entire house is heated. It is possible to use other modelling tools (e.g. SUNREL) to model a multi-zoned house, but in order to provide the simplicity wanted from ALF3 it was not possible to make this into a multi-zone model. A method was therefore needed to use ALF3 to model only the heated areas of the house. The ALF3 manual suggests modelling the heated areas of the house and increasing the R-value of the internal walls (which then effectively become the external walls) by a factor of 0.5 of the construction R-value of the exterior walls, as they have a conditioned space on the adjacent side.

With the house being considered one zone, internal floors/ceilings are not considered for heat losses. The ALF3 Manual suggests that the whole house be modelled except where it is clear a part of the building is not heated and not insulated, e.g. most garages (ALF3 Manual, Section 5.4.1.1). For this comparison, attached garages were not modelled and conservatories were also excluded unless open to the house.

The excerpt below is from the ALF3 Manual, Section 5.5.2 and is a suggested method of dealing with the one zone model. The manual notes that this is a very coarse adjustment, which does not take into consideration gains and thermal mass in the unheated zones or the area of external walls in the unheated zone:

- *For all the area calculations (floors, walls and roofs) use only the area of the heated and insulated building zones.*
- *Adjust the R-value of the internal walls between heated and unheated zones by adding half of the average R-values of the envelope of the unheated zone.*

Two methods were then tested to determine a possible way of adapting ALF3 to treat the heated zone of the house:

1. The method suggested in the ALF3 Manual, Section 5.4.1.1 was to model the heated zone of the house only and increase the R-value of the internal walls in zone (as mentioned above).
2. The proportion of the house that is heated was determined, and then heating energy calculated using that percentage of the ALF3 heating output for the whole house.

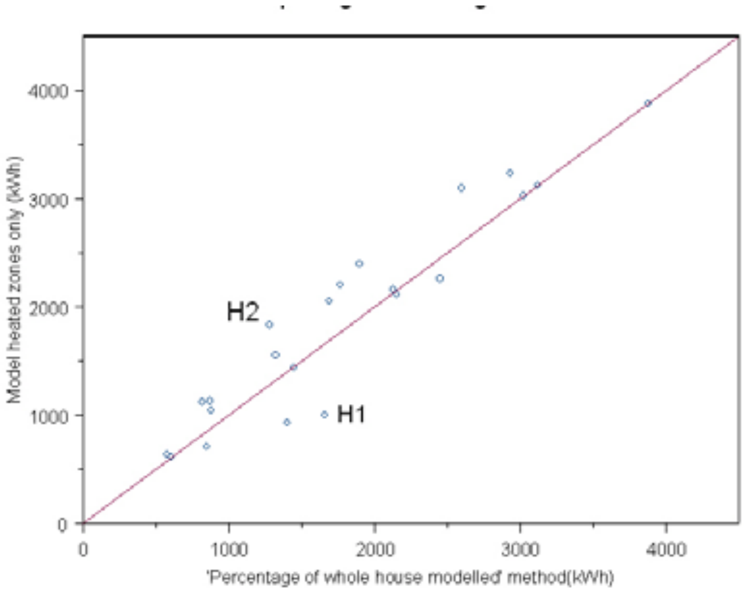

Figure 177: Percentage versus modelled heated zone methods

When comparing the two methods (Figure 177), a strong relationship was found (r^2=0.9). It was decided, after trying both methods on 22 houses, that the percentage method was more simplistic and likely to be just as accurate as the approach suggested in the ALF3 Manual. The energy use by the remaining houses was then assessed using the percentage method.

The two concerns with simplifying the heating to a percentage of the house are with the mass and solar gains. All of the houses in the ALF3 sub-sample are relatively low mass, with those that have concrete slab floors often covering the majority of the concrete with carpet.

This suggests that the differences that occur between the two methods are from the differing amounts of useful solar gains in the heated space of the house.

Two houses were looked at in closer detail – H1 and H2 as shown in Figure 177. The heating energy use for house H1 from the percentage method is higher, and but for house H2 the modelling method gives a higher energy use. The main difference between these two houses is the direction the heated areas of the house are facing for solar gains. The living spaces in H1 face west, while in H2 they face north. Both H1 and H2 are lightweight, rectangular houses with similar insulation and heated spaces on one corner of the building. No obvious reasons for the difference have been identified, and further work will be carried out on a larger sample.

No schedule for overnight heating in ALF3

In ALF3 there is no schedule for heating overnight. The four that are included are:

- morning only
- morning and evening
- daytime
- 24 hour heating.

The HEEP database has 43 out of 346 (12.4%) of houses heating overnight, as the majority of houses that are heated overnight have solid fuel burners.

25.6 HEEP heating energy estimates

On completion of monitoring, space heating energy was able to be estimated for most HEEP houses. Exceptions include:

- Two houses where oil was used as a main heating fuel, which have yet to be included in the space heating energy estimate.
- At the beginning of HEEP monitoring, methods were being used for the first time in some cases. In particular, data for LPG heater use is limited for the earlier houses – Wellington and Hamilton.

All HEEP houses had natural gas, electricity, LPG and solid fuel monitored. Totals of each energy type were monitored, including the hot water separately and any fixed heating appliances such as a wood burner, under-floor heating and gas fires. For one-quarter of houses the appliances (including portable heaters) were randomly selected and monitored on a monthly basis. As portable space heaters were not always monitored separately, it is necessary to estimate the heating energy.

It is difficult to determine space heating energy, for reasons including:

- varying outputs of different heating appliances
- differing occupant heating habits
- lack of stable heating regimes.

25.6.1 Electric heating and reticulated natural gas

Due to these difficulties in determining space heating, it has not been possible to use tools based on static ‘average’ inside temperatures. Instead it has been necessary to develop tools to extract heating energy use from the detailed energy monitoring.

The total electricity and gas use can have the hot water energy use removed, and can then be averaged by weeks, and a linear regression model fitted for energy use versus external temperature. For the purposes of analysis, it was assumed that no significant heating energy was used in the summer months from January to March, and thus the highest energy use in this period could be taken as the base. Energy use over this base can be attributed mainly to space heating, although there will be some extra lighting and cooking use in most houses over winter. There is no accurate way of separating the lighting and cooking use from the space heating at this stage. For this reason there is an unknown error which will vary by house depending on occupant behaviour.

25.6.2 Solid fuel burners

The method for calculating energy usage of solid fuel burners is reported in Section 16.

25.6.3 Portable LPG cabinet heaters

Portable LPG cabinet heaters (LPG heaters) were each measured separately. The majority of households in the HEEP sample with LPG heaters had only one; the remaining ones had two.

The method used to measure LPG heater use was to monitor the operation of each panel of the LPG heater. A description of this measurement method is given in the HEEP Year 4 (Camilleri et al, 2000) and the HEEP Year 6 (Isaacs et al, 2002) reports which also provide some analysis of the use of these heater types. Further analysis of the use of LPG heaters is given in the HEEP Year 7 (Isaacs et al, 2003) and HEEP Year 8 (Isaacs et al, 2004) reports.

As LPG heaters are portable appliances they are frequently brought into (either newly acquired or from storage) or removed from the heated areas of the household. The preparation of an LPG heater for monitoring requires about 30 minutes and was usually completed during the HEEP installation. As the LPG heaters came and went from the sample houses, there was some delay from when a heater was newly introduced into a household to when it was being monitored.

Another source of missing data for the LPG heaters is due to the complex nature of their monitoring. When there were any faults with any of the thermocouples (working loose, connection problems, shorting-out) then often no calculation of the LPG heater energy use could be made.

Simple extrapolation methods have been applied to account for these periods of missing data so that good estimates of the space heating contribution of LPG heaters can be made.

25.7 Comparison of energy use

Comparisons were made between the heating energy from ALF3 and from HEEP. This was not straightforward as ALF3 is a one zone model (i.e. treats the entire house as one single heating zone) and as few New Zealand houses are heated uniformly, adaptations had to be made to correct for this. Two methods were trialled – the ‘heating levels for a zoned model’ and a ‘whole house average temperature’. Neither method can be considered more or less correct than the other.

25.7.1 Heating levels for a zoned model

The average family room temperature during the actual heating period was calculated for each house, as were heating periods during the day and the year. Figure 178 shows spread of the measured average living room temperatures by Regional Council. The dotted black line is at 16°C, the lowest set-point option in ALF3 as well as the lowest recommended temperature by the World Health Organisation (WHO, 1987). The median temperature for each area is above 16°C.

The closest temperature level to the average living room temperature was entered into ALF3, which gives temperature set-point options of 16°C, 18°C and 20°C.

To adjust for the different house temperatures and heating schedules compared with the ALF3 options, the following method was used for each individual house. All houses in the selected sample have been included in this process. According to the author of ALF3, Albrecht Stoecklein, ALF3 reliability will decrease with internal temperatures below 14°C (red dotted line in Figure 178) as the temperature difference between inside and outside is too small and above 22°C as the supporting modelling did not explore this temperature. There are six houses with heating period average temperatures below 14°C and five above 22°C.

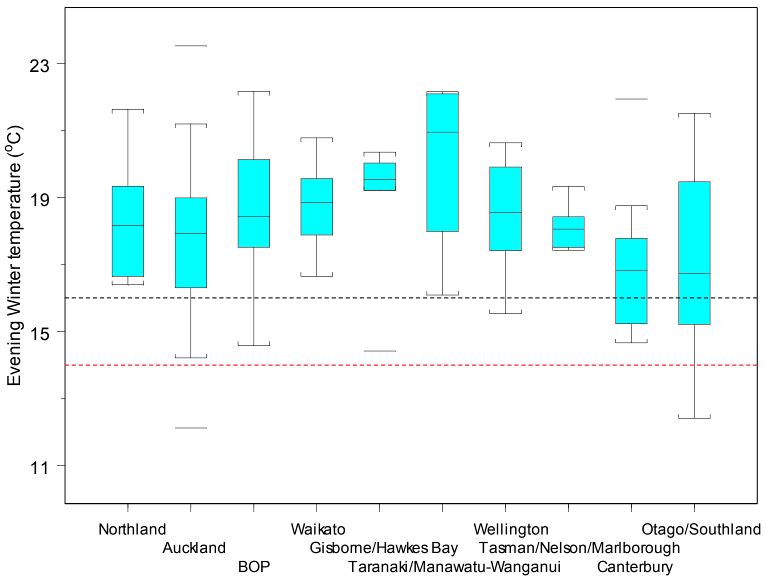

Figure 178: Average living room temperatures during heating times

The method first calculates a ratio using the difference between the actual heating hours and the closest ALF3 option, which for most houses is six heating hours. It then calculates the heating degree hours for both average external and average internal temperatures over the selected heating period.

Heating degree hours are the number of hours heating would have been required at the base temperature (16°C, 18°C or 20°C depending on the house), multiplied by the difference between average inside and average outside temperatures over the heating period. This ratio was then used to adjust the difference in heating degree hours between the two heating schedules (actual and ALF3).

Zones heated

With most New Zealand houses only being partially heated, and ALF3 being a one zone model, a correction method was required to reduce the difference in heated areas of the model compared to the reality of the way New Zealanders heat their homes. The percentage of each house that is heated was determined, and then multiplied by the total heating energy. For example, if 50% of the house was heated then 50% of the total heating energy use was calculated to give a more realistic heating energy use.

This method was tested in the HEEP Year 8 report (Isaacs et al, 2004) and was found to correlate well with the suggested method in the ALF3 manual (Stoecklein and Bassett, 2000) of modelling only the heated areas of the house.

As different spaces are heated to differing extents, each type of space was given a weighting. Bedrooms and utility spaces generally will not be heated as intensively as the family rooms of houses. The family room is where approximately two-thirds of household heaters in HEEP were located. Table 184 gives the weightings for each space.

	Living room	Second living room	Bedrooms	Utility rooms
Weighting	1.0	0.5	0.5	0.2

Table 184: Weighting of spaces for heating

If the second living room is the only one heated, then its weighting is increased from 0.5 to 1.0. If occupants report they heat the living spaces and the utility rooms, then the area of each space would be multiplied by the weighting. In the majority of houses HEEP monitored only the temperatures in one bedroom and one living room, so there is no way of checking whether all reported spaces are actually heated.

Results of this method can be seen in Figure 179 and Figure 180. Both graphs show the same data, the centre line is where ALF calculated heating energy equals the actual heating energy. The red outer lines on Figure 180 show 20% below and above that line. On Figure 179 the red outer lines show ± 2000 kWh. The correlation (r^2) between the heating energy derived from HEEP and the ALF3 model is 16%.

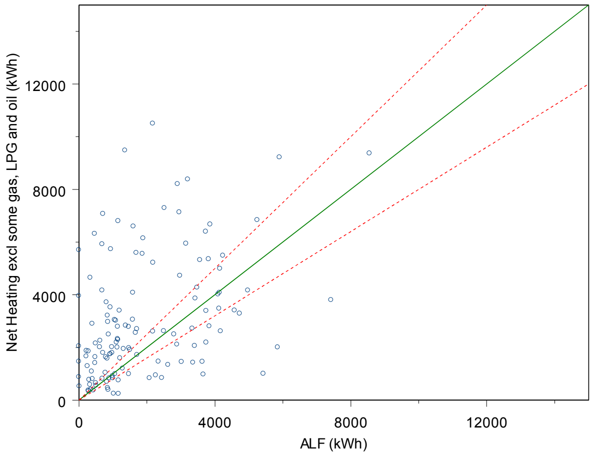

Figure 179: ALF3 vs. reality – 20% lines

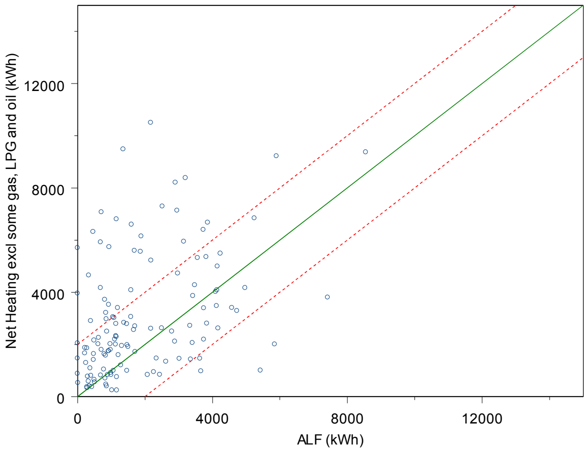

Figure 180: ALF3 vs. reality – 2000 kWh lines

Explanations of the calculation of net heating energy are given in Section 16.

Issues with reported house heating

Self-reported information has been used to establish the proportion of the house that was heated. For the majority of HEEP houses, only the temperatures in the living room and master bedroom were monitored, so it is not possible to compare the measurements and the self-reported information.

In addition, the occupant-provided information on what rooms are heated varies for each house. Often the occupants only provided general information on the bedrooms, living room or utilities heating and to what schedule. Information often was not collected (or volunteered) on which specific bedroom(s), living room(s) (if there is more than one) or utility room(s) are heated. A certain amount of checking can be carried out to determine what is possible or most likely e.g. if the house only has fixed heaters in some rooms, then it is more likely that those rooms will be heated than other rooms. Similarly, two occupants are unlikely to heat all five bedrooms.

During data entry, only the self-reported information was input. In some cases the database entries were then double-checked using measurements, photos of the house and appliances.

With the different field staff and the occasional occupant filling in the questionnaire, the answers were not always consistently recorded e.g. the heater description may have been written as the appropriate coding was not clear. During data entry it was only possible to enter a code, so the heater with only a description could have been missed. To ensure the database is as accurate as possible, cross-checking with photos and other information collected during installation is required.

25.7.2 Heating levels for the whole house

There are problems with determining what spaces are heated and to what extent e.g. are the bedrooms heated for as long as the living room and to the same temperature? Therefore, a second method was developed based an overall house temperature.

This overall representative house temperature was calculated for the heating times by using the average of the two living room temperatures, the average of the bedroom temperature and the average of the external temperature to account for the unheated spaces. Heating energy was then calculated for the whole house.

Figure 181 shows the distribution for this overall average house temperature by region. As expected, the average house temperature temperatures (Figure 181) are lower than the living room temperatures (Figure 178). With so many houses showing average temperatures below 14°C, it would be expected that the reliability of using ALF3 would be affected. The red dotted line is at 14°C and the black at 16°C.

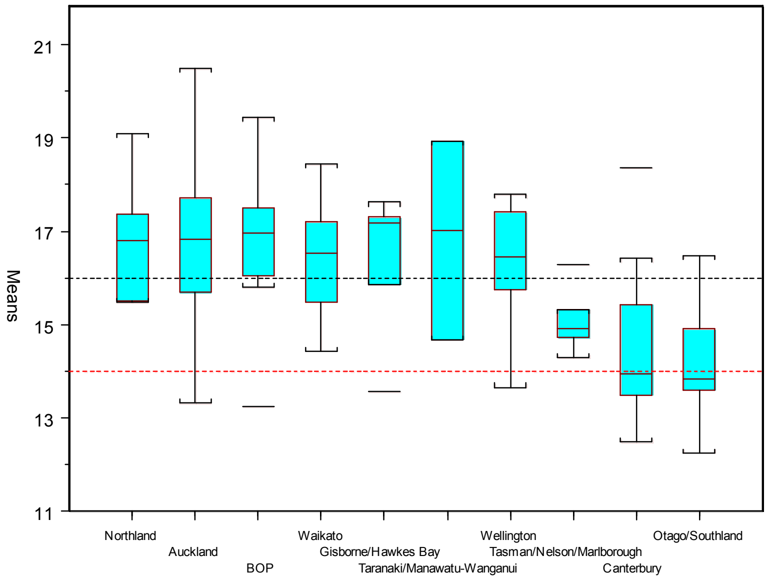

Figure 181: Average house temperatures during measured heating times

The results of this method can be seen in Figure 182 and Figure 183 with the centre line on each graph representing X=Y. The red lines on Figure 182 show + and – 20% and on Figure 183 they show + and – 2000 kWh.

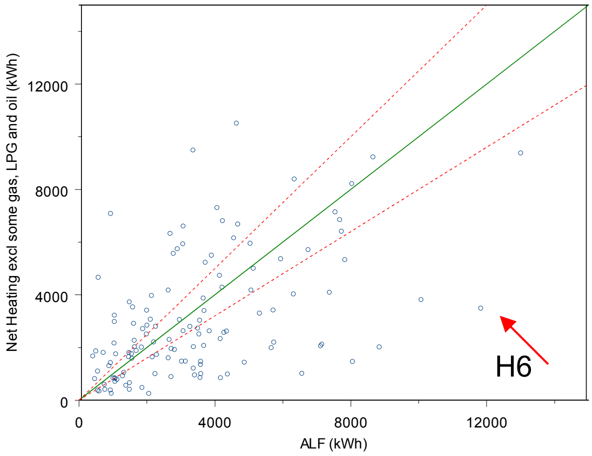

Figure 182: ALF3 vs. reality – 20% lines

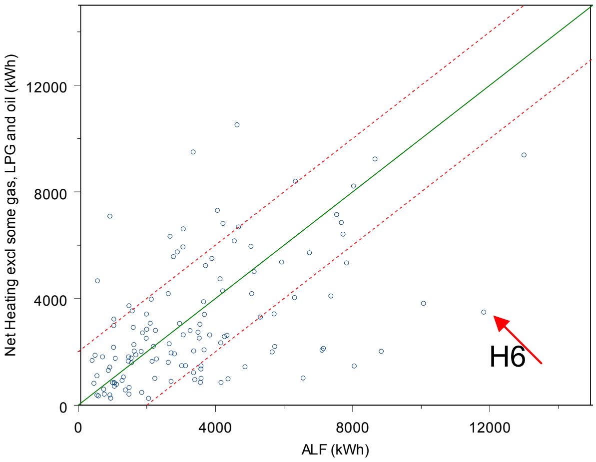

Figure 183: ALF3 vs. reality – 2000 kWh lines

There is a better correlation overall (44%) than the results of the heated zone method, although these improvements are not found for all houses. It must also be remembered that the net heating energy estimate from HEEP has an unknown degree of error.

One house that does not work well for this method is House 6 (indicated by an arrow in Figure 182 and Figure 183), although in the zoned method this house had ALF3 energy within 20% of the HEEP energy estimate.

Possible reasons that the whole house temperature method was not successful for House 6 include:

- Very low heating temperature in a warm climate – ALF3 becomes very sensitive to each slight temperature change. Although temperature was 16°C inside, outside was about 13°C so there is only a small temperature difference and hence a very small change in indoor temperature has a large impact.
- House 6 is a two-storey house with most of the temperature sensors upstairs, as well as most reported heating. Therefore the temperature downstairs (half of the house) will be a lot cooler resulting in an inaccurate whole house temperature. Any multi-storey house could have similar problems.

25.7.3 Examination of models

There are a number of reasons why the HEEP houses cannot be modelled in ALF3 exactly as they are used.

With ALF3 being capable of modelling only one zone, problems arose when choosing the heating schedule and heating level. Although it is possible to model only those areas that are heated unless the house is centrally heated (approximately 5% of the HEEP sample), the spaces that are heated in the house are often heated to differing (and unknown) extents.

ALF3 provides four different schedules for heating, but it is unlikely that occupant use will fit into one of these schedules all the time (or even some of the time). Occupant schedules (as well as the climate) vary and it is unlikely that they switch on or off the heating at the same time each and every day. Very few HEEP houses have time clock controlled central heating (about 5%) or time clock controlled unit heaters.

Houses in real life can be heated overnight or intermittently, while solid fuel burners take a while to warm up and cool down and have varying outputs depending on the quality of the fuel. These issues make it hard to model heating.

There are limits on modelling building components and use of the house cannot always be averaged into the one value that is often needed.

One hundred and thirty-five houses have been used for the comparisons reported here. The full set of 397 randomly selected houses could not be used due to one or more of a number of reasons. In order of significance, these are:

- could not determine heating times
- could not determine heating months
- could not calculate a heating estimate
- could not calculate the area heated for the house
- could not model – insufficient information on house.

25.8 Conclusions

The results of this work provide confidence to support the use of ALF within the HEERA model.

In order to achieve this estimate, it was necessary to closely examine the household space heating use and make appropriate adjustments to the ALF3 assumptions. Three key differences have been identified between the HEEP monitoring and ALF3 assumptions:

- ALF3 predicts space heating energy use for the whole house, where most HEEP households only heat part of their house
- length of heating season (months) – most houses monitored in HEEP appear to heat for a longer period of the year than the ALF3 model
- length of daily heating (hours) – the majority of the occupants in the HEEP sample heat for shorter periods than given in ALF3.

The high space heating energy use houses in HEEP are predominantly solid fuel users. Therefore the HEEP energy estimate is not necessarily as accurate as where the high users have been houses with central or fixed heating, which was often separately monitored for the study.

Two methods for adapting the ALF3 results to work for a house that does not have all rooms heated were tested. Neither can be considered more correct than the other, but different methods will suit different houses depending on their heating patterns.

Overall, ALF3 appears to provide a reasonable estimate of space heating use, but now that we have more information on New Zealanders' heating patterns the regional heating seasons could be altered to match reality better. A shorter heating period in the evening may be more realistic for most current houses, although this may not be as valid for new houses. The possibility of making ALF3 a multi-zone tool could also be considered, although this might take away from the simplicity and ease-of-use of the tool.

Internal gains from appliances, people and hot water standing losses could also be examined in greater detail. The gains from hot water systems are modelled realistically, although they depend on the hot water system e.g. an externally-mounted instant gas system will provide no 'internal' gains. Internal gains from appliances and occupants are realistic, although will vary from house to house.

26. REFERENCES

26.1 HEEP reports

Electronic (PDF) copies of all HEEP executive summaries are available from the BRANZ Ltd website (www.branz.co.nz). Printed copies are available from BRANZ Ltd at the addresses given in Section 1.3 at the current advertised price. The full reference for each report is given below:

Year 1: Stoecklein A, Pollard A and Isaacs N (ed), Ryan G, Fitzgerald G, James B and Pool F. 1997. ‘Energy Use in New Zealand Households: Report on the Household Energy End-use Project (HEEP) – Year 1’. Energy Efficiency and Conservation Authority (EECA), Wellington, New Zealand.

Year 2: Bishop S, Camilleri M, Dickinson S, Isaacs N. (ed), Pollard A, Stoecklein A (ed), Jowett J, Ryan G, Sanders I, Fitzgerald G, James B and Pool F. 1998. ‘Energy Use in New Zealand Households: Report on the Household Energy End-use Project (HEEP) – Year 2’. Energy Efficiency and Conservation Authority (EECA), Wellington, New Zealand.

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Year 5: Stoecklein A, Pollard A, Camilleri M, Amitrano L, Isaacs N, Pool F. and Clark S. (ed). 2001. ‘Energy Use in New Zealand Households: Report on the Year 5 Analysis for the Household Energy End-use Project (HEEP)’. BRANZ *Study Report 11*. BRANZ Ltd, Judgeford, New Zealand.

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26.2 HEEP *BUILD* articles

The BRANZ magazine *BUILD* has published results from HEEP on a regular basis.

Stoecklein A. 1997 "Teenage Daughters and Other Unpredictables" BUILD February/March 1997 pp 36-38.

Stoecklein, A., 1999, "Just how effective is house insulation", BUILD magazine, March/April 1999, BRANZ, Judgeford.

Stoecklein, A., 2001 Year five results of the household Energy End-use Project (HEEP) BUILD 67 Nov/Dec pp 38-39

Stoecklein, A., 2001 Confessions of a researcher BUILD 67 Nov/Dec p 40

Camilleri, M., 2001 NZ homes leak. $120 Million of electricity each year BUILD 64 May/June pp 44-46

Pollard, A., 2001 Getting into hot water BUILD 63 Mar/Apr pp 58-61

Isaacs, NP. 2002. Year 6 results of the Household Energy End-use Project (HEEP). BUILD 73, December 2002/January 2003. Pp68-79

Isaacs, NP. 2003. Are NZ Houses Comfortable? BUILD April/May 2003 pp36-37.

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French L & Isaacs N. 'Houses too hot to handle'. BUILD 100, pp 46-47 June/July 2007.

26.3 HEEP conference papers

A number of the papers presented over the years by the HEEP team are available at no charge in PDF format from the BRANZ website (www.branz.co.nz). Hard copies can also be purchased online from the BRANZ Bookshop on the website. The following list is additional to that in the HEEP Year 9 report, and covers the period 1 July 2005 to 30 June 2006.

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Pollard AR, Camilleri MT, French LJ and Isaacs NP. 2005. 'How are Solar Water Heaters used in New Zealand?' In *Proc. Solar 2005 Renewable Energy for a Sustainable Future – A Challenge for a Post-Carbon World Conference,* 28-30 November 2005, University of Otago, Dunedin, New Zealand, ISBN: 0-473-10937-9 (BRANZ *Conference Paper CP 120*).

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Isaacs N. 2006. 'Energy Exploration at Home – Household Energy End-use Project (HEEP)'. In *Presentation Materials of International Symposium on Urban Energy Infrastructure Development for Mitigating Environmental Impact*. Organised and published by Handai Frontier Research Center, Osaka University, held at Awaji Yumebutai International Conference Center, Japan 28-29 March 2006 (invited international speaker).

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26.4 HEEP Journal Papers

French LJ, Camilleri MJ, Isaacs NP & Pollard AR. 2007. ‘Temperatures and heating energy in New Zealand houses from a nationally representative study – HEEP’. *Energy & Buildings* Vol. 39, No 7, July 2007. Pp770-782.

26.5 Other HEEP references

HEEP also formed a significant part of the following industry presentations:

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Isaacs N. 2006 *Understanding Houses: 1 – Temperature and Water, 2 – Energy Research.* Commissioned seminars presented to Hometech Ltd franchisees’ annual meeting, 25-26 March 2006, Mooloolaba, Queensland, Australia.

Isaacs N. 2006. *NZ Building Code and Domestic Glazing.* Opening address to the Glass Association of ANZ Industry Day, 16 June 2006, Christchurch, New Zealand.

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General presentations on the HEEP research were given to: *Transpower staff* (Wellington, 15 July 2005), *NZIA Otago Public Meeting* (Dunedin, 3 August 2005), six staff visiting New Zealand from the *Municipal Electricity Authority* (MEA), Bangkok, Thailand (Wellington, 12 August 2005), *Parliamentary Commissioner for the Environment staff* (Wellington, 19 August 2005), invited keynote speaker to *Environment Canterbury workshop* (Timaru, 20 October 2005).

Lectures including results of HEEP research were given to students at Victoria University of Wellington, Auckland University, University of Otago, Massey University (Albany Campus).

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Isaacs N. 2005. ‘Health Energy – Some New Insights’. *PHA News* 3(5): 3,4,10 (Nov).

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APPENDIX 1: TABLE OF STANDBY POWER AND ENERGY

For further discussion see Section 21. Appliances marked * were spot measured.

Group	**Appliance**	**Standby power (W)**	**Standby energy (W)**	**Appliances per house (#)**	*Standby energy per house (W)*
Entertainment	Audio component*	3.5	2.2	0.40	0.9
	TV set-top box	13.3	11.8	0.41	4.3
	DVD player*	3.5	1.9	0.10	0.2
	Games console	5.2	3.8	0.21	0.1
	Miscellaneous*	5.1	3.2	0.10	0.3
	Radio*	1.7	0.7	0.43	0.3
	Radio cassette*	1.7	0.7	0.38	0.3
	Stereo	7.1	4.6	1.35	6.2
	Television	5.2	3.1	2.10	6.3
	VCR	9.4	7.5	1.13	9.0
Garage	Door opener*	2.6	1.8	0.18	0.3
	Power tool*	4.7	0.2	0.78	0.2
	Weedeater*	0.8	0.2	0.03	0.0
Kitchen	Bread maker	2.8	2.5	0.24	0.8
	Coffee maker	0.0	0.0	0.30	0.0
	Crockpot	0.0	0.0	0.17	0.0
	Dishwasher	1.6	1.2	0.41	0.5
	Electric grill*	0.0	0.0	0.07	0.0
	Electric oven*	0.0	0.0	0.10	0.0
	Extractor fan*	0.0	0.0	0.07	0.0
	Food processor*	0.6	0.0	0.40	0.0
	Frying pan	0.5	0.4	0.29	0.0
	Jug	1.1	0.8	0.98	0.8
	Microwave	3.6	3.1	0.90	2.8
	Mini-oven*	0.0	0.0	0.13	0.0
	Mixer*	0.1	0.0	0.41	0.0
	Rangehood*	0.4	0.2	0.33	0.1
	Small appliance*	0.1	0.0	0.76	0.0
	Toaster	0.1	0.1	0.84	0.1
	Waste disposal	0.4	0.1	0.10	0.0
	Wastemaster*	0.0	0.0	0.10	0.0
Laundry	Dryer	1.0	0.6	0.64	0.4
	Iron	0.0	0.0	0.71	0.0
	Washing machine	3.1	1.9	0.98	1.8
Miscellaneous	Alarm clock*	1.6	1.1	1.13	1.2
	Burglar alarm*	2.3	1.0	0.12	0.1
	Cell-phone charger*	1.2	0.6	0.26	0.2
	Charger*	1.6	0.5	0.25	0.1
	Cordless phone*	2.0	1.5	0.74	1.1
	Electric blanket	0.0	0.0	0.80	0.0
	Electric organ*	4.1	2.9	0.06	0.2
	Hairdryer*	0.0	0.0	0.34	0.0
	Instant gas water heater*	9.0	11.3	0.03	0.3
	Intercom*	1.5	1.9	0.01	0.0
	Lamp	1.1	0.8	2.52	2.0
	Miscellaneous appliance*	1.3	0.4	0.19	0.1
	Miscellaneous gear*	2.9	1.9	0.06	0.1
	Miscellaneous personal*	0.9	0.3	0.31	0.1
	Sewing machine	0.1	0.0	0.30	0.1
	Shaver*	1.1	0.6	0.06	0.0
	Spa pool	1.1	1.3	0.03	0.0
	Toothbrush*	1.3	0.7	0.08	0.1
	Vacuum	0.5	0.2	0.97	0.2
	Waterbed	2.2	0.9	0.04	0.0
Refrigeration	Freezer	1.8	0.7	0.68	0.5
	Fridge	10.6	4.6	0.66	1.7
	Fridge freezer	15.0	5.3	0.65	4.7
Home office	Answerphone*	3.4	2.7	0.10	0.3
	Computer	7.6	4.1	0.85	4.4
	Monitor*	2.1	1.8	0.12	0.2
	Fax machine*	5.2	3.3	0.25	0.8
	PC peripherals*	3.6	2.8	0.33	0.9
	Printer*	3.3	2.1	0.42	0.9
Space Conditioning	Air-conditioner	0.0	0.0	0.06	0.1
	Dehumidifier	2.1	0.7	0.22	0.2
	Fan	0.1	0.1	0.58	0.1
	Heater	0.4	0.2	1.51	0.3
	LPG heater (fan) *	5.0	6.3	0.01	0.1
	Air fresheners*	1.7	1.2	0.21	0.3

Table 185: Standby power and energy for all measured appliances

APPENDIX 2: ENERGY CONSUMPTION TABLES

The following tables provide the annual kWh (gross energy) for fuels and end-uses which were monitored in a significant number of houses (see Section 2.3). Note fuel oil is not separately included due to the small HEEP sample size.

Location	All fuels	SE	Electricity	SE	Gas	SE	LPG	SE	Solid fuel	SE
Overall	11,410	420	7,800	210	1,060	140	240	40	2,310	270
Auckland	10,660	520	7,970	360	1,870	370	90	30	720	190
Hamilton/Tauranga	10,750	840	7,270	780	1,780	570	120	60	1,580	580
Wellington	10,860	790	7,840	610	2,380	630	200	110	640	260
Christchurch	11,010	750	8,710	500	220	160	320	190	1,750	530
Dunedin/Invercargill	14,580	1,450	10,610	1,010	170	170	820	320	2,980	940
Clusters	11,740	810	7,300	340	530	160	270	60	3,620	550
Warm clusters	9,960	790	6,740	420	500	210	340	80	2,380	520
Cool clusters	13,780	1,170	7,950	490	560	240	190	80	5,050	790

Table 186: Average annual total energy use per house by fuel

Location	All fuels	SE	Electricity	SE	Gas	SE	Solid fuel	SE
Overall	3,260	100	2,440	80	660	90	150	40
Auckland	3,580	200	2,310	180	1,270	260	-	-
Hamilton/Tauranga	3,390	530	2,590	590	660	320	140	60
Wellington	4,610	420	2,350	300	2,240	550	30	20
Christchurch	2,960	210	2,710	210	140	140	110	40
Dunedin/Invercargill	3,100	280	2,840	310	-	-	250	160
Clusters	2,860	140	2,400	100	190	80	260	90
Warm clusters	2,700	170	2,270	100	280	130	150	110
Cool clusters	3,050	220	2,540	180	100	70	370	130

Table 187: Average annual hot water energy use per house by fuel

Location	All fuels	SE	Electricity	SE	Solid fuel	SE	Gas	SE	LPG	SE
Overall	3,820	350	920	190	2,150	250	520	110	240	40
Auckland	3,190	840	1,630	720	720	190	750	340	80	30
Hamilton/Tauranga	2,830	530	280	80	1,430	530	990	360	120	60
Wellington	2,630	730	780	600	610	250	1,230	400	200	110
Christchurch	3,010	690	950	350	1,640	520	90	90	320	190
Dunedin/Invercargill	6,810	910	3,130	420	2,720	820	140	140	820	320
Clusters	4,370	560	420	110	3,360	510	320	130	270	60
Warm clusters	3,080	480	290	140	2,230	450	220	160	340	80
Cool clusters	5,860	830	550	180	4,680	750	440	230	190	80

Table 188: Average annual space heating energy use per house by fuel

Location	All cooking	SE	Range	SE	Lighting	SE	Refrigeration	SE
Overall	900	60	630	50	910	90	1,120	70
Auckland	1,030	100	650	90	1,460	300	1,030	160
Hamilton/Tauranga	910	210	590	190	620	110	1,100	100
Wellington	1,090	340	800	340	880	250	1,220	260
Christchurch	990	160	700	140	530	130	800	170
Dunedin/Invercargill	970	150	740	110	1,550	150	720	280
Clusters	760	70	570	70	680	90	1,260	110
Warm clusters	840	110	620	110	580	110	1,470	140
Cool clusters	620	70	430	60	800	140	1,000	110

Table 189: Average annual energy use per house for selected end-uses

APPENDIX 3: ESTIMATES OF PRECISION IN MULTI-STAGE SURVEYS

It is established below that, in a very general context, the standard error of the estimate of the population mean may be estimated purely from the observed variation in estimates for the first stage units, without any need to estimate the precision of these component estimates. This is of immediate application for the HEEP analysis, in which the variance of the estimates for individual houses would be difficult if not impossible to estimate.

Suppose that from some population P a random sample S of *n* units *i* is drawn, using *n* independent draws at each of which the probability that unit *i* is selected is p_i. Suppose that for each unit a "true" value y_i is defined, so that the sample mean is unbiased for some population parameter η of interest, that is, so that we have $\eta = \sum_P p_i y_i$. In such a situation it can easily be shown that $\frac{1}{n} \times \frac{\sum_{i\in S}(y_i - \bar{y})^2}{n-1}$ gives an unbiased estimator of the variance of the sample mean (1).

Now suppose that the y_i are unknown, even for the units selected in S, but that for each possible sample *s* an unbiased estimator $Y_{i,s}$ of y_i is defined for each *i* in *s*, which estimates y_i with variance $\sigma^2_{i,s}$. The estimators $Y_{i,s}, i \in s$ are assumed to be conditionally independent, given *s*.

Then the sample mean of the Y_i is unbiased for η, and $\frac{1}{n} \times \frac{\sum_{i\in S}(Y_{i,s} - \bar{Y}_s)^2}{n-1}$ is an unbiased estimate of its variance.

Before giving the proof, which is a simple exercise in conditional probability, we shall comment on the range of application of this result. The only real restriction is that of independence of the draws in the "first stage" sample S. This implies that either the sampling is done "with replacement," or that the population P is very large compared to the sample size n. The simple example of exhaustive enumeration shows that the result is false if this condition is violated.

There is no requirement that the estimation method should be the same for each unit selected: for example, if the units were clusters, we could exhaustively sample smaller units, sample middle sized units, and subsample very large ones. Moreover, the method used in any selected unit may depend not only on that unit selected, but also on the other units selected in the sample. For example, we could distribute a final sample of fixed size among clusters selected at random in the first stage, according to the sizes of the clusters obtained.

The proof is an application of the completely general results that the expectation of a random variable is the expectation of its conditional expectation, and that its variance is the sum of the variance of its conditional expectation and the expectation of its conditional variance. Using conditioning on the actual first stage sample obtained, we have

$$\begin{aligned} \mathrm{var}(\bar{Y}) &= \mathrm{var}_S(\mathrm{E}\bar{Y} \mid S) + \mathrm{E}_S\,\mathrm{var}(\bar{Y} \mid S) \\ &= \mathrm{var}_S(\frac{1}{n}\sum_{i\in S} y_i) + \mathrm{E}_S(\frac{1}{n^2}\sum_{i\in S}\sigma^2_{i,S}) \end{aligned}$$

where the bar represents averaging over the observed sample.

Consider now the sample variance *V* of the Y_i, given by

$$(n-1)V = \sum_{i \in S} (Y_i - \overline{Y})^2$$

Writing $Y_i = y_i + e_i$, and expanding, we obtain in the usual way

$$\sum_{i \in S} (Y_i - \overline{Y})^2 = \sum_{i \in S} (y_i - \overline{y})^2 + \frac{n-1}{n} \sum_{i \in S} e_i^2 + ...$$

where .... represents cross product terms with expectation (conditional on S) zero.
Taking expectations conditional on S, we then obtain

$$\mathrm{E}(V \mid S) = \frac{1}{n-1} \sum_{i \in S} (y_i - \overline{y})^2 + \frac{1}{n} \sum_{i \in S} \sigma_{i,S}^2 \text{ ,}$$

and finally taking expectations over S, and dividing though by n, we obtain

$$\mathrm{E}\left(\frac{V}{n}\right) = \frac{1}{n} \mathrm{E}_S \left(\frac{\sum_{i \in S} (y_i - \overline{y})^2}{n-1} \right) + \mathrm{E}_S \left(\frac{1}{n^2} \sum_{i \in S} \sigma_{i,S}^2 \right) \quad (2)$$

Comparing this expression with (1), we see that the second terms are identical. That the first terms are equal is asserted by the basic result quoted in the statement of the theorem.

The need for independent draws in obtaining the sample may now be seen to be simply that the finite population correction required to bring the first term of (2) into alignment with the first term of (1) is not appropriately applied to the second term of (2). Consequently, if we are prepared to neglect this finite population correction, the result may still be used where sampling is done without replacement.

APPENDIX 4: SAMPLING VARIANCE OF THE SURVEY ESTIMATOR

Here we calculate the theoretical variance of the estimator used, in a special case. This establishes that the method used is competitive with an alternative method, in which a smaller set of appliances is monitored continuously.

Suppose that in a population P of N units, a random sample of n units is taken. Suppose that a fixed time period is divided into T equal time periods, and that some variable takes the value x(i,t) per unit time for unit i and time period t. It is required to estimate the population mean $\mu = \frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T} x(i,t)$.

Suppose that within each unit of the sample, for each time period, *x(i,t)* is observed with probability *p* and not observed with probability 1-*p*, where *p* is known. Define random variables

$$Q(i,t) = \begin{Bmatrix} 0 & \text{if } x(i,t) \text{ is not observed} \\ \frac{1}{p} & \text{if } x(i,t) \text{ is observed} \end{Bmatrix}$$

$$X^*(i,t) = Q(i,t)x(i,t)$$

Let $X^* = \frac{1}{NT}\sum\sum X^*(i,t),\ Q = \frac{1}{NT}\sum\sum Q(i,t)$

Then E(*Q*) = 1 and $\mathrm{E}(X^*) = \mu$.

Now assume that the $Q(i,t), i = 1...n, t = 1...T$ are mutually independent for all i and t.
Define μ_i and$\frac{2}{i}$as the mean and variance (using divisor *T*-1) respectively of *x(i,t)*within unit *i*. It should be noted that whereas μ_i is independent of the number of intervals into which the fixed time period is divided, σ_i^2 is not, but will increase with *T*. σ_i^2 does, however, have as upper bound the variance of the continuous time series underlying the time averages *x(i,t).*

Let $\mu = \frac{1}{N}\sum_1^N \mu_i$ (as before), $\bar{\sigma}^2 = \frac{1}{N}\sum_1^N \sigma_i^2$, and $\sigma_\mu^2 = \frac{1}{N}\sum_1^N (\mu_i - \mu)^2$.

Then $R = \frac{X^*}{Q}$ is asymptotically (in *n*) unbiased for μ, with asymptotic variance

$$\mathrm{var}(R) = \frac{\sigma_\mu^2}{np}\left(p + \frac{1-p}{T} + \frac{T-1}{T^2}\left(\frac{\bar{\sigma}^2}{\sigma_\mu^2}\right)\right)$$

Proof of Method

We use the general result $\mathrm{cov}(X,Y) = \mathrm{E}_C(\mathrm{cov}(X,Y \mid C) + \mathrm{cov}_C(\mathrm{E}(X \mid C), \mathrm{E}(Y \mid C))$. When *X* and *Y* are the same, this yields the corresponding result for variances, quoted in Appendix 1.

First we consider each house separately, conditioning on the sample size within that house and then applying the above formula.

We set $\overline{Q}_i = \frac{1}{T}\sum_t Q(i,t),\ \overline{X}_i{*} = \frac{1}{T}\sum_t X*(i,t)$, to obtain, conditional on the sample size *M*, say:

$$\begin{aligned}
E(\overline{Q}_i \mid M) &= \frac{M}{pT} \\
E(\overline{X}_i{*} \mid M) &= \frac{M\mu_i}{pT} \\
\mathrm{var}(\overline{Q}_i \mid M) &= 0 \\
\mathrm{var}(\overline{X}_i{*} \mid M) &= \frac{1}{T^2}\left(1-\frac{M}{T}\right)M\frac{\sigma_i^2}{p^2} \\
\mathrm{cov}(\overline{Q}_i, \overline{X}_i{*} \mid M) &= 0
\end{aligned}$$

We note that these expressions are correct for *M*=0, and that σ_i^2, which is undefined when *T*=1, may as well be defined as 0.

Noting that M has a binomial(*p,T*) distribution, we then use the covariance formula to remove the conditioning on *M*, giving

$$\begin{aligned}
E(\overline{Q}_i) &= 1 \\
E(\overline{X}_i{*}) &= \mu_i \\
\mathrm{var}(\overline{Q}_i) &= \frac{1-p}{pT} \\
\mathrm{var}(\overline{X}_i{*}) &= \frac{1-p}{pT}\left(\frac{T-1}{T}\sigma_i^2 + \mu_i^2\right) \\
\mathrm{cov}(\overline{Q}_i, \overline{X}_i{*}) &= \frac{1-p}{pT}\mu_i
\end{aligned}$$

Now consider the unit *i* to be selected at random. The above expressions are then conditional expectations and variances, conditional on the house selected. Using the covariance formula again, we obtain (noting that the subscript *I* is now a random variable)

$$\begin{aligned}
E(\overline{Q}_I) &= 1 \\
E(\overline{X}_I{*}) &= \mu \\
\mathrm{var}(\overline{Q}_I) &= \frac{1-p}{pT} \\
\mathrm{var}(\overline{X}_I{*}) &= \sigma_\mu^2 + \frac{1-p}{pT}\left(\frac{T-1}{T}\overline{\sigma}^2 + \frac{\sum \mu_i^2}{N}\right) \\
\mathrm{cov}(\overline{Q}_I, \overline{X}_I{*}) &= \frac{1-p}{pT}\mu
\end{aligned}$$

Since the population size N is assumed large, we can now ignore finite population corrections, and obtain the variances and covariances of the sample means by dividing by n, giving

$$
\begin{aligned}
E(Q) &= 1 \\
E(X^*) &= \mu \\
\operatorname{var}(Q) &= \frac{1-p}{npT} \\
\operatorname{var}(X^*) &= \frac{\sigma_\mu^2}{n} + \frac{1-p}{npT}\left(\frac{T-1}{T}\overline{\sigma}^2 + \frac{\sum \mu_i^2}{N}\right) \\
\operatorname{cov}(Q, X^*) &= \frac{1-p}{npT}\mu
\end{aligned}
$$

At this point we pause to note that for sufficiently large T the variance of X* approaches $\frac{\sigma_\mu^2}{n}$, which is what we should get if all units were monitored continuously. This may be compared with $\frac{\sigma_\mu^2}{np}$, which is what would be obtained by devoting the same amount of monitoring effort to the continuous monitoring of *np* units.

The results so far have been exact. We now apply the asymptotic results for the variance of a ratio:

$$
\frac{\operatorname{var}(X/Y)}{(\mathrm{E}X/\mathrm{E}Y)^2} = \frac{\operatorname{var}(X)}{(\mathrm{E}X)^2} - 2\frac{\operatorname{cov}(X,Y)}{(\mathrm{E}X)(\mathrm{E}Y)} + \frac{\operatorname{var}(Y)}{(\mathrm{E}Y)^2}
$$

to the ratio $R = \frac{X^*}{Q}$.

This results in

$$
\operatorname{var}(R) = \frac{\sigma_\mu^2}{n} + \frac{1-p}{npT}\left(\frac{T-1}{T}\overline{\sigma}^2 + \sigma_\mu^2\right)
$$

which we rearrange to enable easy comparison with the alternative method:

$$
\operatorname{var}(R) = \frac{\sigma_\mu^2}{np}\left(p + \frac{1-p}{T}\left(1 + \frac{T-1}{T}\left(\frac{\overline{\sigma}^2}{\sigma_\mu^2}\right)\right)\right)
$$

Comments

The results are clearly asymptotic, for when T=1 the variances of the two estimators appear equal. The variance of a mean of a sample of *np* units is, however, known to be always less than the average variance of the mean of a sample of random size averaging *np,* since the harmonic mean (of sample size) never exceeds the arithmetic mean. The difference is however of $O(n^{-2})$, whereas the asymptotic formula we have used is correct only to $O(n^{-1})$.

Secondly, the ratio estimate is always preferable to the uncorrected use of *X**, its effect being to replace the uncorrected mean square of the μ_i by the corrected mean square in the variance formulae. Use of the ratio estimator is highly desirable for another reason: in extreme cases it is possible for *X** to fall outside the range of the data on which it is based, whereas this is not possible for *R*.

The condition for the ratio estimate to be more efficient than continuous monitoring of *np* units is

$$\frac{\overline{\sigma}^2}{\sigma_\mu^2} \leq T$$

Although $\overline{\sigma}^2$ increases with T it is bounded above, so that this will always be achieved for sufficiently large T.

APPENDIX 5: EXAMPLE OF BIAS ARISING THROUGH FAILURE TO TAKE ACCOUNT OF VARYING PROBABILITIES OF SELECTION WITHIN HOUSES

Prepared by John Jowett

Suppose that we are interested in the total energy used by televisions and computers.

Suppose

a) All dwellings have a television but only 60% of dwellings have a computer.
b) We have a random sample of 100 dwellings, all with televisions and 60 with computers.
c) We can use one transponder in each dwelling.
d) For "reasons of efficiency" we want to put transponders on 50 computers and 50 televisions.
e) The occupants of a dwelling without a computer spend an average of 2 hours per day watching television. The occupants of a dwelling with a computer spend an average of 1 hour per day watching television and 1 hour per day on the computer.

Then the average hours of television watching per dwelling per day in the population is $0.4 \times 2 + 0.6 \times 1 = 1.4$.

To meet the efficiency requirement we then place transponders on computers in 50 of the 60 dwellings with computers, and on televisions in the remaining cases. If this is done, the average time spent watching television for the sample is $(40 \times 2 + 10 \times 1) \div 50 = 1.8$, a considerable over-estimate of the true figure of 1.4.

This bias has arisen because our sample of televisions over-represents televisions in dwellings without computers.

The most obvious way of dealing with this is recognise that dwellings with and without computers may have different television watching patterns, and to stratify the population into dwellings with and without computers, provide a separate estimate for each group, and weight the two estimates appropriately in the final estimate. This is reasonable when we are just dealing with two appliances. But in the HEEP survey there are many types of appliances being considered, and we would end up with more or less as many strata as dwellings, with one house per stratum, and no idea of the appropriate weighting to use.

An alternative method is to calculate the probability of selection for each appliance, and weight each estimate by dividing by this probability of selection. In the example, the probability of selection for the televisions was 1 in houses without a computer, and 1/6 in houses with one.

The estimate then works out to $\dfrac{(40 \times 2 \div 1) + (10 \times 1 \div \frac{1}{6})}{40 \div 1 + 10 \div \frac{1}{6}} = \dfrac{140}{100} = 1.4$ as required.

This procedure, of weighting each power consumption by dividing it by the probability of its being selected, is the basis of the estimation method used in the HEEP survey. The considerable complications it involves are necessary to avoid biases of the type illustrated in the example. An advantage is that it allows considerable flexibility, for example monitoring heaters with lower probability in summer than in winter (as was in fact done).

APPENDIX 6: HISTORICAL REVIEW OF HOT WATER

Prior to the 1945 Census there is no statistical data on the availability of hot water in New Zealand homes. In that Census, for the first time a question was asked about the availability of hot water supply. Although the precise question has changed over time, Figure 184 plots the responses from all available Censuses (N.Z. Department of Statistics 1952, 1959, 1964, 1969, 1975, 1980, 1982b, 1987b. Statistics NZ 1997). It should be noted that the 1986 Census asked only whether the hot water supply was ‘Electric’, ‘Gas’, ‘Other’ or ‘No hot water supply’ – this does not permit a detailed analysis of the ‘Other’ fuel source in 1986 as for the other Censuses.

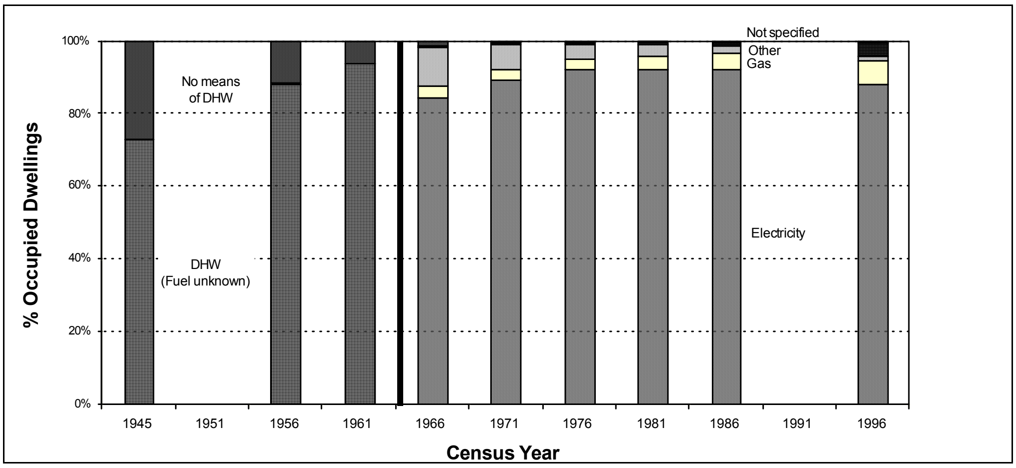


Figure 184: NZ Census 1945-1996 Domestic Hot Water by fuel type

In 1945, 1956 and 1961 the Census question was only concerned with the availability of hot water service. In 1945 26.9% of households reported that they had no means of hot water service – they would have batch heated water in a container either on the stove or in the laundry ‘copper’. When it took so much work – carrying inside not only the water but also the heating fuel – it is not surprising that bathing was limited to once a week, and most often to ensure cleanliness for Sunday church.

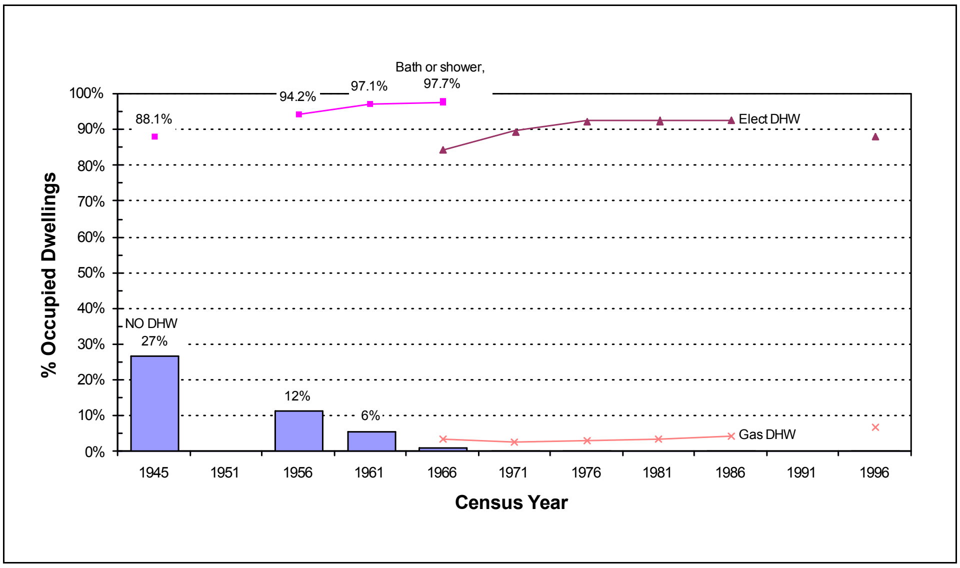


Figure 185: NZ Census 1945-1996 % Dwellings with no DHW

Figure 185 shows that in 1945, 27% of households lacked a hot water service, but over the next decade this proportion reduced so that by 1956 only 11.6% of households lacked a hot water service. The proportion fell to 5.9% by 1961 and 1.1% by 1966. By 1996 – the last Census in which a question on hot water service was asked – there were only 4,917 dwellings (out of the then total of 1,276,332 'Private Occupied Dwellings') which lacked a hot water supply.

Even in 1945 88% of households had either a bath or shower – suggesting this amenity was present in at least some of the 15% of households that lacked a hot water service. In those houses the hot water would have been 'batch brewed' – heated in a pan or basin on the stove, and carried to the bath, just as would have been the case 50 years earlier. The proportion of homes with a bath or shower grew rapidly, and by 1966 (the last year in which this question was asked) one or the other was found in 97.7% of households.

As from 1966 almost all houses had a hot water service, the Census could then ask about the type of fuel being used – and in the large majority of cases it was electricity. In 1966 84.3% of households used electricity as the fuel to provide hot water. This increased to 89.5% in 1971 and again in 1976 to 92.5%. It stayed at this level for the 1981 and 1986 Censuses, but fell to 88.1% in the 1996 Census as gas increased its market share. The question was not asked in 1991.

Figure 186 shows the proportion of houses reporting only one fuel and the numbers for each individual fuel. In the 1996 Census a total of 1,046,886 households (82% of all households) reported only one fuel used for hot water provision – 951,759 (75% of all households) reported only electric water heating, 83,646 (7%) reported only gas water heating, 10,821 (0.8%) only solid fuel water heating and 660 (0.05%) only solar water heating.

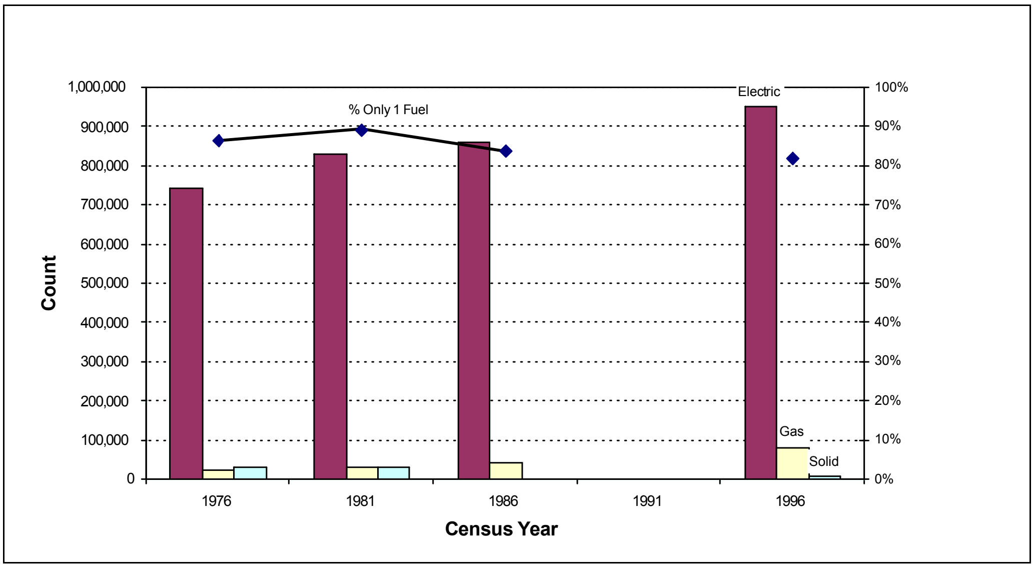


Figure 186: NZ Census 1976-1996 Dwellings with only one DHW fuel

Figure 186 also shows that there has been a decline in the proportion of households with only one hot water fuel. The highest proportion (89%) of households with only one fuel occurred in the 1981 Census, which reduced to 84% in the 1986 Census, and reduced again to 82% in the 1996 Census. This may be due to some households wishing to have higher security of hot water supply, and achieving this by choosing a different secondary fuel. For example, the proportion of houses with both electric and another hot water system with a different fuel has increased from 11% of dwellings in 1981 to 15% in 1996.

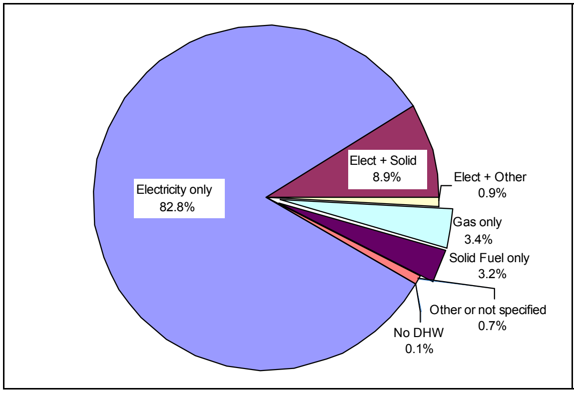


Figure 187: 1981 Census DHW Fuels

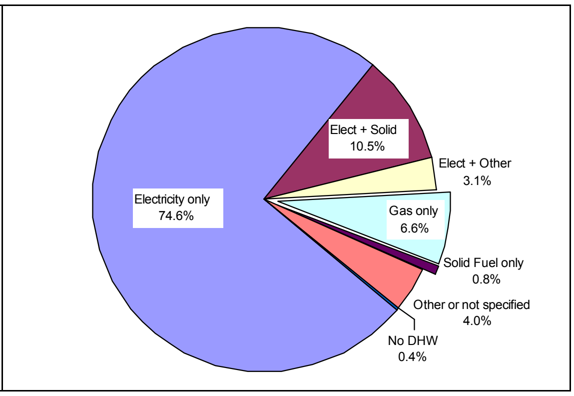


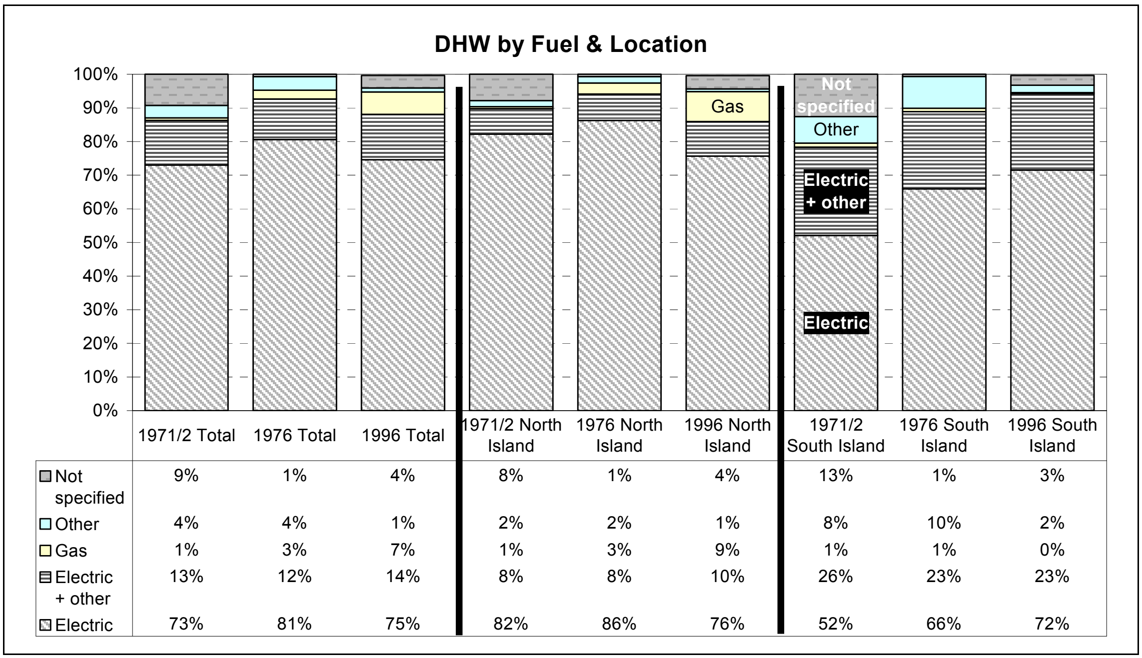
Figure 188: 1996 Census DHW Fuels

Figure 187 and Figure 188 provide the proportions of households reporting use of different fuels for domestic hot water (NZ Dept of Statistics 1982b, Statistics NZ 2005).

The 'fall' over the two Censuses in the proportion of electric-only hot water is matched by the increase in electricity with solid-fuel and the use of gas (mains and bottle).

There is also an increase from 1981 to 1996 in the 'Other or not specified' category from 0.7% to 4%, but the majority of this is in the number of households that did not specify what fuel was used for hot water, increasing from 4,689 (0.5% of total dwellings) to 47,127 (3.7%) in 1996.

The number of homes reporting 'no hot water service' has increased from 1,329 in 1981 to 4,917 in 1996. These are in both cases less than 0.5% of the total number of dwellings, and it is unlikely that this reported change has any significance.



	1971/2 Total	1976 Total	1996 Total	1971/2 North Island	1976 North Island	1996 North Island	1971/2 South Island	1976 South Island	1996 South Island
■ Not specified	9%	1%	4%	8%	1%	4%	13%	1%	3%
□ Other	4%	4%	1%	2%	2%	1%	8%	10%	2%
□ Gas	1%	3%	7%	1%	3%	9%	1%	1%	0%
▤ Electric + other	13%	12%	14%	8%	8%	10%	26%	23%	23%
▧ Electric	73%	81%	75%	82%	86%	76%	52%	66%	72%

Figure 189: Changes in reported DHW fuel by region

Figure 189 compares the hot system by fuel for the 1971/72 Household Electricity Study, the 1976 and the 1996 Censuses. Although electric systems are dominant nationally, Figure 189 shows that this is due to their dominance in the North Island which had 74% (940,566) of all households in the 1996 Census. In the North Island electric or electric + other fell from 90%

of households in 1971/72 to 86% in 1996. In the South Island there has been a steady increase, with electric or electric + other rising from 78% to 95% in 1996. Interestingly, the proportion of electric + other in the South Island fell from 26% to 23%.

Until piped water

> "The morning bath should be cold, the evening one tepid"[48]

A pot of water collected from the nearby stream, river, lake or well and heated over an outside open fire has been used since time immemorial. Early European settlers shifted from an outdoor fire to a chimney with an indoor opening, but it was not until the 1860s (a mere twenty years after New Zealand had become a colony of Great Britain) that piped water was available in the main New Zealand cities.

By the mid-1860s piped water was laid to at least the central city areas in Dunedin, Wellington and Auckland[49], but it took another twenty years before piped water was available in at least the homes of the wealthy. It was not until the early 1900s that centrally-provided and treated piped water started to become commonplace. The designs for the first 'workers dwellings' built at Petone under "The Workers' Dwellings Act 1905" to provide affordable homes included provision for on-site water storage tanks (Fill 1984). Even in the more affluent suburbs of Wellington water storage tanks, fed from roof collection, were required in 1908.

Even in England, it was not until sometime after 1870 that piped water reached the bathroom (Wright 1960 p 218) although basins were not common until after about 1918 (p222). After about 1900 bathrooms become more common, often with all the fittings and plumbing on one wall. Even in expensive hotels, it was not until the early 1900s that rooms with a bathroom became common – for example not until 1906 for the Ritz in Paris. The provision of running water was not enough – once used it had to be removed, and it was not until the provision of full waste systems that the need to 'bucket away' the water was removed.

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NEW
RAILWAY HOTEL,
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FIRST-CLASS ACCOMMODATION
For
VISITORS AND BOARDERS.

☞ Baths—Hot and Cold—on every Landing.

TARIFF £2 2s

F. HARRISON,
Proprietor.

Figure 190: First Class Hotel 1899[50]

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[48] Brett's Colonists' Guide and Cyclopaedia of Useful Knowledge" Ed. Thomson W. Leys. Auckland: H. Brett, "Evening Star Office" 1883. (Reprint: Capper Press, Christchurch, 1980.) pp 450-451

[49] See: www.wellington.govt.nz/services/watersupply/history/history.html
www.aucklandcity.govt.nz/auckland/introduction/bush/chronology.asp
www.cityofdunedin.com/city/?page=water_su

[50] Source: Otago Witness, 31 October 1899 p4

Figure 190 illustrates that in 1899 a tourist heading for "Harrison's New Railway Hotel", West Melbourne in 1899 was offered "First-class accommodation" with "Baths – Hot and Cold – on every Landing". In 2007, the "Tiger Backpackers at the Railway Hotel" advertising[51] doesn't even mention the availability of hot water – it is just taken for granted.

Until piped water was available in the home, hot water continued to be provided by a 'batch' process, whether based around a kerosene tin on the (coal or wood) stove or hung from a hook over an outside open fire (Lee 1977).

The kettle or pot on top of the solid fuel stove meant hot water was readily available in amounts suitable for washing or cleaning. Larger quantities of hot water for the washing of clothes or humans took far more effort. The once-a-week family bath required the heating of large amounts of water, either on the stove or in the copper – and of course the transport of that water to the portable bath and its removal once the family had all washed (Mr Fred Freeman, quoted in Fell, 1984). Often the family bath occurred on Saturday night, so all would be clean for church the next day.

Specialised, dedicated equipment was coming – the laundry 'copper'. This large copper container, when full, held about 14 gallons (60 litres) of water, and was permanently mounted in a concrete or brick stand in the laundry or wash-house. A fire was lit underneath, and after some hours of firstly filling the copper and then heating the water, clothes could be 'boiled' using home made (in later years, store-brought) soap.

> **5. Washing copper**
> (a) Use. For boiling clothes in
> (b) Care. Fill two thirds full before lighting the fire, and put out the fire before emptying. Scour with salt and vinegar, then wash and dry, or rub with kerosene.
> (c) Cost, with cast iron frame, 14 gallons, from £4 5s.
> **6. Boiler stick.** Use part of a broom handle.
> (a) Use. To poke down clothes or lift them from the copper.
> (Whitcombe & Tombs, 1923 p. 143)

The 1923 cost of £4 5s for a copper with a cast iron frame (Whitcombe & Tombs, 1923) was equivalent to $350 in 2006 (Reserve Bank of NZ CPI Inflation Calculator www.rbnz.govt.nz).

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[51] For more information see www.tigerbackpackers.com, who kindly provided the modern photograph

Figure 191: 1930s Laundry Copper

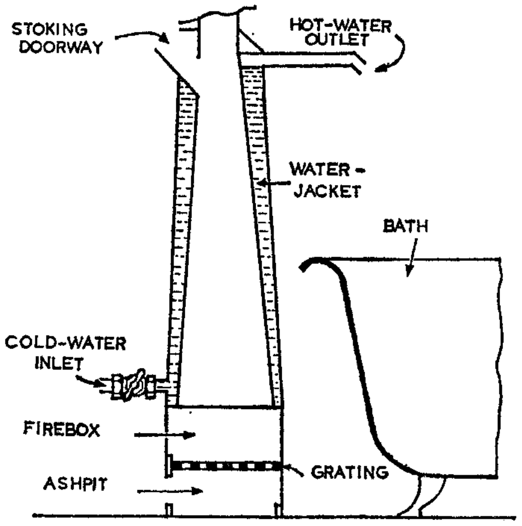

Figure 192: Chip heater

Figure 191 illustrates a washing copper from a 1930s Wellington house. The copper inner is approximately 400 mm deep and 500 mm in diameter, with a 60 mm lip. The concrete support is 840 mm high, enclosing both the copper inner and the firebox. Note the closed cover over the firebox opening, and the open ash cleaning slot beneath. Smoke from the firebox is removed by the chimney at the rear. The inefficient combustion (due in part to the close contact between the fire box and the cold surface of the copper) requires a cleaning slot in the chimney, as well as releasing excess particulates into the atmosphere. Water is provided to the copper by the cold water tap (on right Figure 191). As more houses were fitted with a main hot water supply, the copper could still be used, but now without requiring a fire to bring the water to temperature (tap on left Figure 191).

Purpose built water heaters could be free-standing, such as the batch-feed chip heater shown diagrammatically in Figure 192 or part of the stove such as the piped, 'push-through' water heater shown in Figure 193 where the water could come from the rain water tank (NZTCI 1964).

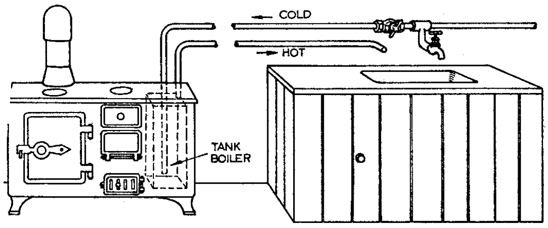

Fig. 207 The push-through method of conveying hot water to a point such as the kitchen sink

Figure 193: Push-through water heater

Beginnings of piped hot water

The provision of water and sanitation were closely tied together. From the 1910s, indoor toilets became common, but it was still many years before either the house joined up to the outdoor toilet or an indoor toilet was available, in the majority of NZ homes (Salmond 1986). By the 1945 Census, 67% of New Zealand homes had a flush toilet, although this grew quickly – by the 1956 Census 81% of homes had a flush toilet and by the 1966 Census (the last time this question was asked) 94% of homes were equipped (N.Z. Department of Statistics 1952, 1959, 1969).

By 1917, as illustrated in Figure 194, the school domestic science course could state (Lesson XI) that "*no modern house is complete without a hot water service connection with the kitchen range*" (Whitcombe & Tombs 1917). The fundamentals illustrated in Figure 194 still form the basis for the majority of New Zealand houses served by a low pressure hot water system – albeit fuelled by electricity rather than iron pipes in the back of the kitchen range. The course book describes the key features as:

(1) A cold water tank placed at a high level, either on or near the roof
(2) An iron boiler or arrangement of iron pipes to provide a large heating surface at the back of the fire grate
(3) A cylinder for storing hot water; and
(4) The necessary pipe connections

The cold water supply could come either from the cold water tank or from the street mains.

By the 1923, second edition of the 'Southern Cross Domestic Science' course, it was found that a system based on solely the kitchen range was not adequate: *A distinct improvement in the above service can be made by having an additional boiler behind the dining room or sitting-room fire. Then the household is rarely if ever without a plentiful supply of hot water* (Whitcombe & Tombs 1923).

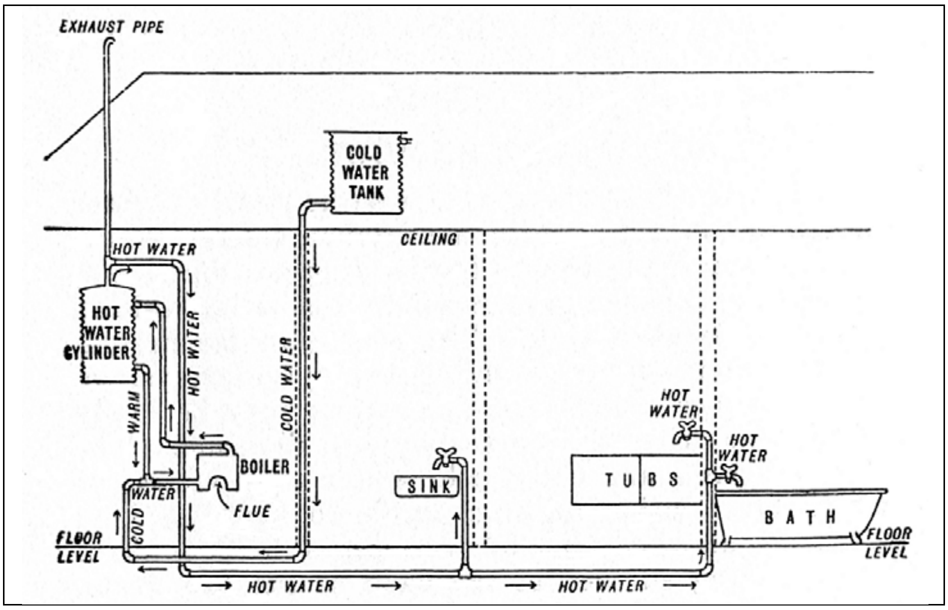

Figure 194: Low pressure household hot water system (1923)

Even today, many homes have water heating from solid fuel burning in a "wetback" to open or enclosed solid fuel burners, especially in areas where space heating is needed for a significant part of the year.

The term ‘wet-back’ is uniquely used in New Zealand to describe *a heat exchanger fitted at the rear of an open fire or stove for providing hot water* (Milton 1994) or “*a wood or coal stove, incorporating water-heating capability*” (Orsman 1997)[52] The comparable Australian term would be ‘auxiliary water heater’ (Milton 1994) while in England it would be labelled as a ‘back boiler’ (Beattie 1966).

History of electric hot water

New Zealand household use of electric hot water heating dates back to 1915, when Lloyd Mandeno (then the Tauranga Borough engineer, but later a major force in the development of electricity in New Zealand) developed the first storage hot water heater for use in the first all electric house:

> *“…Lloyd Mandeno then got stuck in and built the system. He made the hot water container of heavy gauge galvanised iron and fitted two elements, one 350 W and one 500 W. This sat in a larger container, around which he packed a 6 inch thick layer of screened pumice for insulation before placing it under the roof above the ceiling, with short drops of concealed pipe leading to the sink and the bathroom”* (Rennie 1989)

The fatal flaw did not become obvious for a couple of years, when the galvanised iron corroded through, and the hot water followed (Mandeno 1974). The solution – a copper cylinder – remains the basis for the low pressure electric hot water cylinder still used in most New Zealand homes (Rennie 1989).

On 25 October 1923, Mandeno patented the first New Zealand electric hot water cylinder – illustrated in Figure 195, taken from the patent documents (Mandeno 1923). This was not the first electric water heater in the world – the US Patent and Trademark Office has storage type electric water heaters with continuous flow (as opposed to batch heaters) dating from at least 1909 (Patent 938,237 Issue Date: October 26, 1909) – but it was an important step[53].

As with many inventions, others were developing similar designs. Figure 196, taken from the patent documents for U.S. patent 1,612,270 shows a similar style of heater, although lacking any insulation and many other features of Mandeno’s design. The invention in Figure 196 was awarded a patent on 28 December 1926, although the invention was filed on 5 June 1923.

Some points of interest in Figure 195:

- **no separate thermostat** – the heated water lifted a small disk inside pipe ‘5’, permitting the convection of heated water into the storage tank and its replacement by cold water from lower in the tank
- the **external element inside case** ‘14’ – this allowed the pipe to be automatically descaled by the movement of a chain or disk attached to the heated water release disk, and presumably replacement without removing the cylinder from the system. The heating wires were insulated by asbestos and mica – both naturally occurring electrical insulants.
- use of **tank insulation** (number ‘18’) – the tank was insulated with pumice or other appropriate material.

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[52] The term wetback is used in a derogatory sense to refer to an illegal immigrant “*wetback orig. and chiefly U.S., an illegal immigrant who crossed the Rio Grande from Mexico to the U.S*” (Oxford English Directory, 1989)

[53] See: www.uspto.gov US Patent Office, www.iponz.govt.nz NZ Intellectual Property Office

- **corrugated tank and bottom dome** (number '1') – provided more strength than flat material. Hot water system patents earlier than 1910 show neither tank insulation nor tank corrugations.

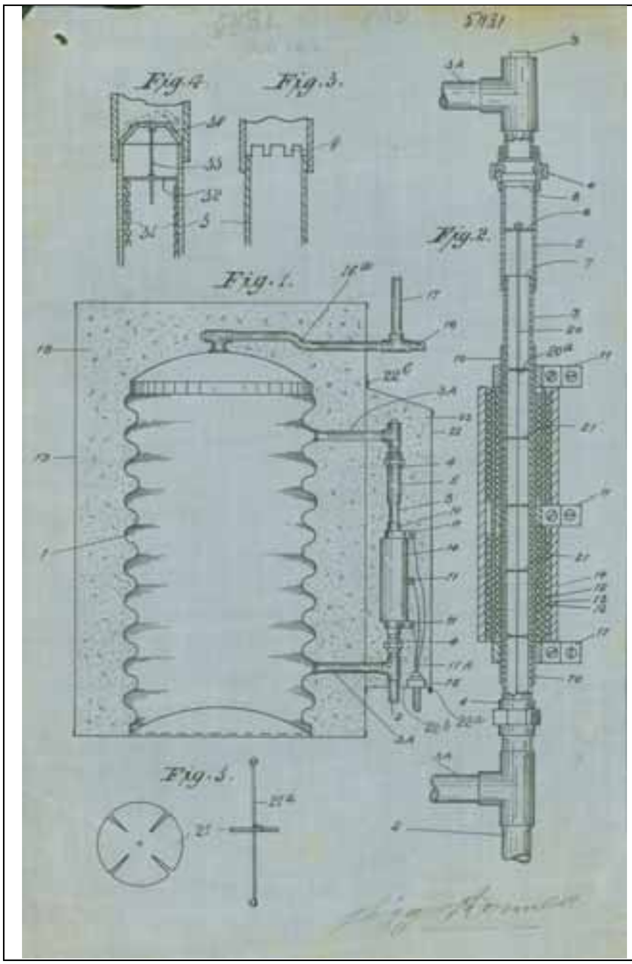

Figure 195: "An Improved Electrical Water Heater" (1923) NZ Patent 51131

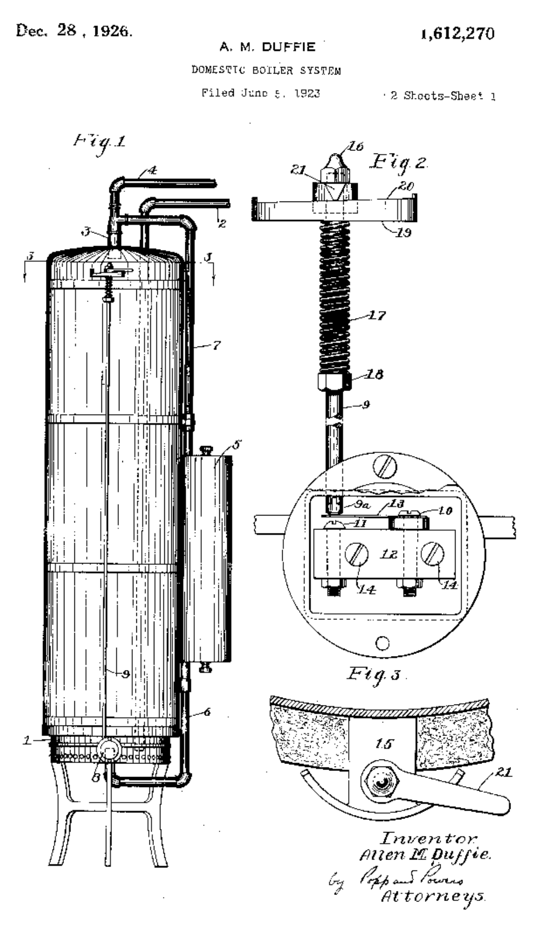

Figure 196: "Domestic Boiler System" (1926) US Patent 1,612,270.

The domestic price of electricity halved between 1923 and 1935 which, coupled with the lack of coal gas 'smell' and a more modern image, rapidly increased market penetration. Electric load management could be achieved by a consumer operated switch – permitting the choice of either hot water or the cooking range, but not both at the same time (Rennie 1989).

By the late-1940s, the modern home cook book provided detailed electrical guidance for the householder with little knowledge of electricity:

> *The size of heater required is dependent on two factors:—*
>
> 1. *Quantity of hot water required.*
> 2. *Time in which heating must be accomplished.*
>
> *Water heating during off-peak load hours is generally procurable at cheap rates. Hours of use are usually from 10 p.m. to 7 a.m. All day water-heating service is also generally procurable at reasonable rates.*
>
> *For night heating the size of electric element required is approximately 1 kW per 20 gallons storage capacity. For 24 hours service this may be halved, i.e., 500 watts, or 600 watts will be found to be ample. Recently there has been considerable development in storage cylinders of the quick recovery* (Whitcombe & Tombs, 1948)

A 40 gallon (180 litres) cylinder with only a 1.2 kW heater can take up to 8 hours to provide a full tank at 60°C. No problem if the main hot water loads were large and intermittent – washing dishes, washing clothes or a bath for the household – but this was not the sole issue of concern.

The Preface to NZSS 720:1949 (NZSI 1949) states:

> *that of the total power consumption in New Zealand 32% is used by thermal storage water heaters of the type covered by the specification. On the basis of a careful examination of the position it is estimated that the installation and use of inefficient heaters is responsible for the wastage of electric power equal to 8.9% of the total amount generated in the Dominion.*

For a modern comparison, HEEP estimates electric hot water uses 31% of household electricity (Isaacs et al. 2006), while the Energy Data File reports residential electricity is 25.5% of total electricity use (MED 2006) – suggesting domestic electric hot water currently consumes 8% of total electricity use (compared to 32% some 55 years ago).

By the 1960s electric water heaters were used domestically, commercially and in dairy sheds. Storage cylinders were generally 30 (136 litre) to 40 (181 litre) gallons, fitted with an electrical heating element varying from 0.75 kW to 2 kW capacity, the majority being of the order of 0.75 kW to 1 kW (Speer 1962).

New Zealand was in a unique situation – electricity generation was peak power constrained but as the majority of generation was from hydro stations, only in times of water shortage was there an energy problem. Originally, electricity for water heating was sold on a fixed annual charge, irrespective of consumption, but severe power restrictions resulted in changes. Metering was made compulsory along with the fitting of thermostats (Speer 1962).

Until 1967 electric supply authorities paid for bulk supply solely on the basis of peak demand, providing a strong incentive for control. Storage hot water systems were recognised as providing an ideal opportunity for load management, as the loading statistics showed that under normal circumstances they operated on supply for an average of only 12 to 14 hours per day (Speer 1962).

Time clock controls had been first installed on storage hot water cylinders in the 1920s, and were followed by ‘pilot wire’ controls (a separate signal wire being installed in each house) in the 1930s. The ‘ripple control’ system (where a signal at a special frequency is feed through the power lines and detected by a tuned relay in the house) was first introduced in 1949 by the Waitemata Electric Power Board, and then quickly spread throughout the country (Rennie 1989).

Changing patterns of behaviour and occupant expectations have lead to different demands on the hot water supply. Dishwashers are present, and most likely have replaced hand washing, in 44% of houses (Statistics NZ 2004h), while automatic washing machines and improved laundry detergents have led to a shift away from hot or warm water washes to cold water washing. The most important shift is that the weekly bath has been replaced by the daily shower – this now requires a constant stream of constant temperature warm water which may not be achievable at a safe temperature with only a small cylinder.

Nowadays a range of different electric hot water systems are available. Instant water heaters (either open vented or in-line) can turn cold water into warm water in a small unit which can be mounted close to the point of use, eliminating the need for both hot and cold water piping. These systems require larger heater elements (4 kW to 14 kW) and heavier duty wiring than the more common storage water system[54]. Storage electric water heaters are available in a range of sizes from 25 litres to 400 litres with single elements from 1.2 kW to 6 kW. These produce hot water at rates from 0.3 $L.min^{-1}$ (20 litres/hr) to 1.7 $L.min^{-1}$ (100 litres/hour)[55].

Compared to an immersion element water heater, an air source heat-pump hot water system provides up to three times the hot water from a given amount of electricity. A 275 litre, mains pressure, heat pump cylinder for outdoor installation (including a booster immersion element for cold climates) costs $5,099, three times the price of a conventional 300 litre mains pressure, dual immersion elements, outdoor installation cylinder at $1,665 (both prices include GST) (Plumbing World 2006).

History of gas hot water

Reticulated coal gas became an important energy source for cooking and heating. Coal gas was first extracted from coal at a plant in Auckland in 1862, and by the end of the decade gasworks were operating in Wellington, Christchurch and Dunedin. The cost of manufactured gas reduced as the network and demand grew. By 1888 the Auckland Gas Company could boast that coal gas was the lowest cost method of lighting. Figure 197, based on the Auckland Gas Company data, compares the deflated cost of the different lighting fuels to the current retail price of natural gas. Natural gas is still one third the real cost of the 1888 coal gas.

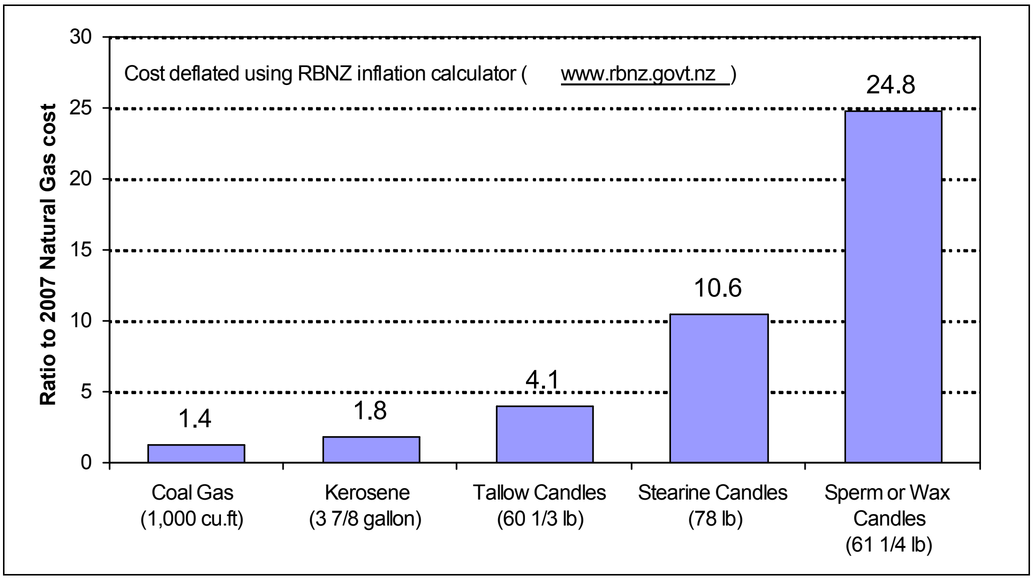

Figure 197: 1888 Lighting Fuel Cost Comparison

By 1900, coal was the main source of energy in New Zealand. Production exceeded 1 million tonnes in 1900, nearly all produced from underground mines by large numbers of men using picks and shovels. The "State Coal Mines" were established in 1901, and coal production continued to increase rapidly, doubling to 2 million tonnes by 1910. Electricity reticulation expanded after World War 1, when there were 56 gasworks in the country, but coal still accounted for more than 50% of the primary energy market in 1940[56].

By the end of Word War Two there were 46 gasworks still operating, with some 200,000 consumers (residential, commercial and industrial) (Veart 2000) with a total of 403,334

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[54] (e.g. www.instanthotwater.co.nz, www.atmor.co.nz)

[55] see 'Rheem Hot Water Manual' available from www.rheem.com.au

[56] "History of coal mining" www.crownminerals.govt.nz/coaL.min^{-1}ing/history.html, accessed 8 June 05

permanent and private dwellings (NZ Dept of Statistics 1952). The number of consumers declined to 100,000 by 1956. By 1965 there were only 33 operating plants. The discovery of natural gas at Kapuni, Taranaki in 1959 was the start of the renaissance of gas, but it was not until 1971 that it was delivered to residential consumers. The delay included not only full testing and proving of the resource, but also the construction of a pipeline throughout the North Island. Then, some 86,000 premises plus a number of large industrial complexes had to be converted from coal gas to natural gas (Veart 2000). The discovery of the Maui field in 1969 allowed the development of large scale gas-based projects, as well as expansion of the gas pipeline.

Year	Pounds	shillings	pence	$2005 (CPI adjusted)
1867	1	-	-	$85.60
1873	-	15	10	$85.78
1883	-	12	6	$86.31
1893	-	10	0	$77.79
1903	-	7	6	$52.62
1913	-	5	9	$37.16
1923	-	7	10	$30.82
1933	-	7	2	$34.86
1943	-	7	2	$24.74
1953	-	8	8	$19.17
1957	-	9	1	$17.62
1962	-	9	10	$16.68
1963	-	10	1	$16.72
2005	Wellington Natural Gas			$24.33

Table 190: Christchurch Gas Company - Gas cost £ per 1,000 ft³

Table 190 compares the price of gas in Christchurch from 1867 through to the closing of the gas works in 1963. The charge per 1,000 cubic feet has been converted to $2005 using the Reserve Bank of New Zealand inflation calculator. For the purposes of comparison the current charge for natural gas in Wellington is also provided. It can be seen that there was a steady reduction in the real price of gas over the period, and even today the price of natural gas is higher than the CPI adjusted price of coal gas from the 1930s.

The South Island remained isolated from the natural gas pipeline network, and in 1991 only Dunedin was sending a reformed gas based on LPG through the old pipelines, while Nelson and Invercargill provided LPG bottles (Veart 2000). Nowadays bottle or tank LPG is widely available throughout the entire country. In the South Island only central Dunedin (Otago Citigas[57]) is supplied with Tempered LPG (TLP) while Christchurch, Queenstown and Wanaka[58] central business districts are on LPG vapour from a centralised LPG facility. Some housing estates in the South Island also have LPG vapour supply. Other domestic and commercial customers not connected to the natural gas pipeline use tanks filled, or delivered, by a dedicated LPG transport industry.

Coal gas was commercialised in 1812 in England, but it was not until the 1850s that it was used in specific appliances for heating water, and not until the late 1860s that the hot water boiler built into the kitchen range became common. The first ‘geyser’ (or ‘califont’) was produced in England in 1868 and the design evolved over the next 30 years. The early geysers could not stand high internal water-pressure, and so one was required at each point of use. The first ‘multi-point pressure geyser’ was produced in 1899, but it was not until the invention of the gas-heated hot water storage tank, complete with thermostat, that competition between different would-be-users of the hot water could be managed (Wright 1960).

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[57] see: http://www.toddenergy.co.nz/te/pages/main/gas/industrial/warminguptheearts.htm

[58] see: http://www.rockgas.co.nz/3-reticulation.asp

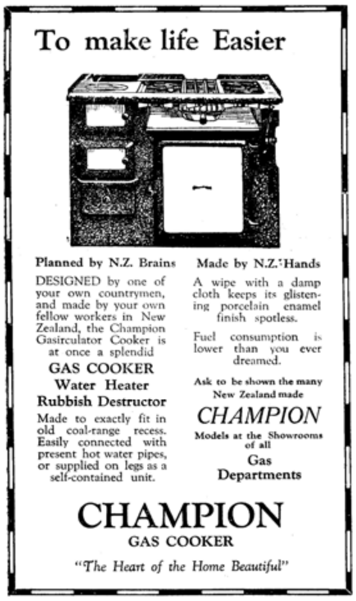
Away from the stove, the stand-alone 'geyser' could fume away, provided both town gas and running water were available, but even then its use does not appear to have been widespread in New Zealand. Apart from the smell of burnt gas, there was always the possible excitement of an explosion if the gas initially failed to light (Wright 1960). The well-appointed gas kitchen of 1923 would be complete with gas stove, gas califont and gas light. Califonts were also common in bathrooms, supplying hot water to the bath.

Gas storage water heaters were available by the 1930s, as illustrated by Figure 198 and Figure 199 (Connor 1930). Figure 198, an advertisement for the 'Mercer' gas storage water heater, shows an insulated tank that is no doubt capable of supplying *hot water in abundance any hour day or night for every purpose*. The kitchen gas stove, even if not fuelled by coal or wood, could still provide household hot water, as illustrated by the 'Champion' advertisement in Figure 199.

With increasing distribution of electricity and the associated decline of the coal gas industry in the 1950s, electricity rapidly became the dominant fuel. It was not until natural gas became available in the 1970s that gas started to make a comeback for water and space heating (Williamson & Clark 2001). Even in 2004, only 14% of New Zealand homes have a mains gas connection (Table 25, Statistics NZ 2004h) although large bottle (45 kg) LPG gas is being used in non-reticulated areas for hot water supply.

A New
Water Heater
HEATED BY GAS
Automatic, Wonderfully Efficient
and Economical

THE MERCER
GAS STORAGE WATER HEATER
Supplies Hot Water in abundance any hour
day or night for every purpose; cost of fitting
is low. A special Gas Tariff is obtained
when the heater is installed
ENQUIRE PARTICULARS FROM YOUR GAS CO.
Manufacturers J. MERCER & SONS Ltd., 54 Oxford Terrace, Christchurch



To make life Easier

Planned by N.Z. Brains

DESIGNED by one of your own countrymen, and made by your own fellow workers in New Zealand, the Champion Gasirculator Cooker is at once a splendid

GAS COOKER
Water Heater
Rubbish Destructor

Made to exactly fit in old coal-range recess. Easily connected with present hot water pipes, or supplied on legs as a self-contained unit.

Made by N.Z. Hands

A wipe with a damp cloth keeps its glistening porcelain enamel finish spotless.

Fuel consumption is lower than you ever dreamed.

Ask to be shown the many
New Zealand made
CHAMPION
Models at the Showrooms
of all
Gas
Departments

CHAMPION
GAS COOKER
"The Heart of the Home Beautiful"

Figure 198: 1930s 'Mercer' Gas Storage Water Heater[59]

Figure 199: 1930s 'Champion' Gas Cooker, Water heater & rubbish destructor[59]

No monitored data on household use of gas (either manufactured or natural) for domestic hot water heating have been found. Gas industry statistics, whether from the industry or Central Government, refer to 'consumers', a term which includes not only residential but also commercial and industrial consumers.

A 1971 report evaluating the future of manufactured gas in New Zealand (W.S. Atkins & Partners 1971) provides an estimate of future (1976) gas use for three major purposes –

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[59] "Hilda Connor's Answer to the Everyday Question: What Shall We Have for Dinner To-day? With General Cooking Instruction for Every Type of Gas Ranges and Advice on Family Housekeeping." The Wanganui Chronicle Co. Ltd 1930

cooking, water heating and space heating. As no New Zealand gas use data were available, estimates of consumption were based on 'figures used by the U.K. Gas Council and various Area Boards'. Water heating was estimated to consume 150 therms[60] per year after adjustment accounting for higher ambient temperatures, while cooking was estimated at 80 therms per year. The U.K. space heating gas use was higher than then found in New Zealand, but was considered to give a 'reasonable assessment' of future space heating loads as the use of central heating increased. The U.K. space heating gas consumption of 500 therms per year for 4200 Degree Days to a 60°F base converts to 0.119 therms per DD (60°F).

End-use	1976 Gas kWh/yr e.g. Blenheim	HEEP Gas kWh/yr Wellington	Ratio 1976 :HEEP
Cooking	2,344	3,993	59%
Water heating	4,395	5,732	77%
Space heating	8,734	5,060	173%
Total	**15,473**	**14,785**	105%

Table 191: Average gas by end-use: projected 1976 use & HEEP use

As the 1971 report lists only the 15 locations then producing manufactured gas, this limits the opportunity for comparisons. Blenheim has been selected for comparison to the HEEP Wellington; Blenheim has 1429 DD (16 °C) compared to 1416 DD (16 °C) for Wellington. Table 191 gives the 1976 Blenheim gas use projection from the 1971 report (W.S. Atkins & Partners 1971) and the gas use from HEEP for the houses that use gas for that purpose.

Compared to the HEEP Wellington gas use, the 1976 estimates are low for both cooking and water heating, but high for space heating. Overall, the 1976 estimate is only 5% higher than the actual Wellington use. The lack of detailed long-run residential gas use data is a major constraint in evaluating further opportunities for natural gas use.

A range of gas storage and continuous flow hot water heaters are now available. Gas storage water heaters range in volume from 135 litres to 360 litres consuming gas at rates from 35 MJ/hr (10 kW) to 200 MJ/hr (56 kW), while providing hot water flows from 3 to 13 L.min^{-1} (averaged over an hour). Gas continuous water heaters consume 80 MJ/hr (22 kW) to 250 MJ/hr (70 kW) while providing a hot water flow from 10 to 32 L.min^{-1}[61].

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[60] Conversion: 1 therm = 105.5 MJ = 29.3 kWh

[61] See data sheets available on www.gas.co.nz, accessed 10 June 05.

APPENDIX 7: CENSUS DHW QUESTIONS

Table 192 lists the various Censuses in which questions were asked about hot water supplies or heating, and Table 193 provides the actual question asked (Statistics 2001a). Note that the 1986 Census question did not permit respondents to differentiate the 'other' fuel type.

Dwelling Form Question	**1945**	**1951**	**1956**	**1961**	**1966**	**1971**	**1976**	**1981**	**1986**	**1991**	**1996**	**2001**
Water Supply												
hot water service	✓		✓	✓	✓	✓	✓	✓	✓		✓	
Heating of Dwelling												
water heating of main supply					✓	✓	✓	✓	✓			
water heating of secondary supply							✓	✓	✓			

Table 192: NZ Censuses historical summary 1945-2001 – hot water questions

Census	**Topic**	**#**	**Question**
1966	DHW	10	State type of hot water service used (electric, gas etc.). (Add "shared" to the answer where use is shared by occupants of other flats etc.)
1971	DHW	11	State type of hot water service used (electric, gas etc.). Add "shared" to the answer, where use is shared by occupants of other flats etc.
1976	DHW	7	Water Heating (a) State type of hot water supply, for example, electric, gas, fuel oil: (b) If a second type is used, please specify Notes: This question refers to a hot water supply available from a piped system or from a tap fitted to a water heater, including all types of gas califonts. "Second type" refers to an additional or supplementary hot water supply available from one or more taps. For example, where the main supply is an electric hot water cylinder, "second type": could be a coal range, chip heater or wet-back. Do not include electric jugs or kettles.
1981	DHW	7	Type of Hot Water Supply (*):Tick box which applies: Electric Gas (mains) Wood, coke or coal Solar Other or nil – specify e.g. oil fired, NIL
1986	DHW	7	What type of hot water supply do you have in this dwelling? Tick one or more boxes: Electric Gas Other (such as wood, solar) No hot water supply
1996	DHW	15	Tick as many circles as you need to show which of the following are ever used in this dwelling for **water heating**. no water heating ever done in this dwelling electricity mains gas bottled gas wood solar heating other fuel(s) – Print fuel(s) (Note: If you heat water with a wet-back, show the fuel(s) used)

Table 193: NZ Censuses 1945-1996 – text of hot water questions[62]

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[62] Census questionnaires are available from the Statistics New Zealand website: www.statistics.govt.nz

APPENDIX 8: INTERNATIONAL REVIEW OF SHOWER WATER FLOW RATES

A literature review of shower water flow rates found very few references to actual measurements at the appliance level. The majority of work, internationally and in New Zealand, has examined total household water use, not end-uses. This Appendix (originally in the HEEP Year 7 report (Isaacs et al. 2003) provides references to American, Australian and English research results.

New Zealand

The only survey found, Hendtlass (1983), investigated the differences in total water use between houses with and without solar water heating, based on time-of-day and length-of-use reported in a user-completed survey. It did not report on actual water use.

The Water End Use and Efficiency Project (WEEP) (Heinrich 2006) investigated water use in a sample of twelve Kapiti Coast homes. The sample does not claim to be representative of New Zealand, but provides the only available detailed water end-use data.

Heinrich (2006) found that the average shower time was 7.8 minutes throughout the year with an average of 0.7 showers per person per day. The amount of water used in the shower can be reduced substantially in a number of homes, by installing a low flow shower head. The four low pressure supplied showers had an average flow of 7.2 litres per minute while the mains pressure system shower had an average flow of 15.8 litres per minute. The homes with small children had a lower shower usage than homes without, but the bath usage tended to be higher.

America

During 1996-1999 the American Water Works Association Research Foundation (AWWARF) supported a major research study to understand how households use water. Dataloggers were attached to water meters in 1,188 homes in 14 cities across the USA and Canada (Mayer et al. 1999[63]).

It was found that about 42% of the water was used indoors, and the remaining 58% used outdoors. The mean per person indoor daily water use was 260 litres (including leakage), including water use estimates by appliance:

- toilet water use was estimated at 70 litres per person per day
- clothes washer use was 57 litres/person/day
- shower use was 44 litres/person/day
- direct tap use was 41 litres/person/day
- leaks accounted for 36 litres/person/day
- baths were 5 litres/person/day
- dishwasher use was 4 litres/person/day
- other domestic use was 6 litres/person/day.

The research investigated the use of low-flow shower heads – these are shower heads designed to restrict flow to a rate of 9.5 L.min^{-1} (2.5 US gallons per minute) or less. Table 194 summarises the reported results for showers, with the average shower flow calculated from the average water use and shower time.

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[63] Project Summary available at www.awwarf.com/research/topicsandprojects/execSum/241.aspx

Table 194 shows that average shower time increased by 25% for the houses with low-flow shower heads, compared with the houses with non-low flow showerheads, the total water use reduced by 34%.

Shower head type:	Average shower time	Average shower water use	Derived average shower flow
Low flow	8 min 30 sec	33 litres/person/day	3.9 L.min^{-1}
Non low-flow	6 min 48 sec	50 litres/person/day	7.4 L.min^{-1}

Table 194: North America – shower water use

Australia

Harrington & Foster (1999) note that there is little data on regional variation in usage patterns for hot water. They suggest showers will typically comprise between 40% to 60% of hot water usage for personal washing. Table 195 provides a summary of the data they collected.

Source	Average duration per person	Frequency per household	Flow rate
Perth (MWA 1985)	8.1 minutes	2.3 /day	
NSW (ABS 1987)		16 /week	
Sydney (Yann 1990)	7.3 minutes		10 to 17 L.min^{-1}
QLD – winter (SRC 1993)	8.6 minutes	3.2 /weekday	
QLD – summer (SRC 1993)	8.1 minutes	3.7 /weekday	

Table 195: Australia – shower water usage

The values from Yann (1990) given in Table 195 suggest water use for an average shower in Sydney is between 73 and 124 litres.

The Water Corporation of Western Australia undertook a ‘Domestic Water Use Study’ in Perth during 1998 to 2001 (Loh & Coghlan 2003). They found difficulties in obtaining accurate information from householders on the efficiency rating of their showers (i.e. A, AA etc), with the result that the only meaningful distinction possible between shower types was whether one or more water-efficient showers (of any type) was owned or not. Table 196, taken from that study, gives water consumption for each type of shower i.e. conventional normal flow and water-efficient shower roses.

In the case of the normal flow showers, there is no significant difference between water usage (litres per shower) by the residents in either single or multi-residential households. There is also no significant difference between shower durations for a normal flow or water-efficient shower rose. The average shower lasts about seven minutes (ranging from 6.7 to 7.3 minutes).

Type of residence	Shower type	L/day	L/shower	Min/shower	L.min^{-1}
Single residential	Normal flow	152	60	7	9
	Water-efficient	135	48	7	7
Multi-residential	Normal flow	113	64	7	9
	Water-efficient	110	58	7	8

Table 196: Perth – shower water use

Loh & Coghlan (2003) suggest, as observed from Table 196, that water savings of one to two litres a minute could be achieved by changing to a water-efficient shower rose. Thus for a seven-minute shower, a water savings of seven to 14 litres can be achieved, amounting to a water savings of between 2.6 and 5.1 kilolitres/person/year.

A comparison with the similar study carried out in 1981/82 (Metropolitan Water Authority 1985) shows that average shower water use has increased from 47 litres/person/day to 50 litres/person/day, although there has been a major reduction bath water use down from seven litres/person/day to only one litre/person/day.

United Kingdom

'Water UK' (the U.K. water industry trade association) reports that a typical shower uses 35 litres of water[64].

The UK "Office of Water Services" (OFWAT) reports that this would cost on average £0.05 (about $NZ 0.15), compared to £0.09 ($NZ 0.27) for heating the water (OFWAT 2002).

In August 2000 the Environment Agency commissioned a report of shower use in the UK[65]. The manufacturers reported:

- Electric showers (7.5kW to 10.8kW) – flow rate of 3 to 7 $L.min^{-1}$ (62% of sales)
- Mixer showers – flow rate of 5 to 15 $L.min^{-1}$ (30% of sales)
- Power showers – flow rate of 12 to 20 $L.min^{-1}$ (8% of sales)

The responses to a questionnaire sent to staff in water industry related organisations were that:

- 80% of respondents owned showers of which 73% were fixed (not detachable hoses)
- 72% of people spend less than 10 minutes in a shower.

The mean shower flows were:
Mains water pressure - 7.6 $L.min^{-1}$

- Mixer (attached to bath taps) - 6.1 $L.min^{-1}$
- Electric - 5.5 $L.min^{-1}$
- Pumped - 9.6 $L.min^{-1}$
- Non-specific (other) - 5.3 $L.min^{-1}$.

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[64] Accessed through http://www.water.org.uk/index.php?raw=262 September 2003

[65] Pers. com. from Rob Westcott, Principal Water Analyst, Water Demand Management, UK Environment Agency. 17 October 2003.

APPENDIX 9: PENSIONERS HOT WATER USE

WEL Energy Trust sponsored the monitoring of 12 pensioner houses in Hamilton, as an additional case study to the 17 Hamilton HEEP houses. These houses were monitored from February 2000 to January 2001 to the full level of HEEP monitoring, which included a comprehensive survey and building audit, and monitoring of total and hot water energy use, LPG heating, and temperatures in the living room and bedroom. This was originally reported in the HEEP Year 5 report (Stoecklein et al. 2001).

Hot water energy demand

Pensioner households used more than 60% less energy for hot water than non-pensioner households in the study. Very few pensioner households used more total hot water than non-pensioners households. Table 197 shows the comparison between the two groups.

Hamilton HEEP households	**Total Hot Water Demand (kWh/day)**	**Energy Used for Delivered Hot Water (kWh/day)**	**Standing Loss (kWh/day)**
Pensioners	3.8 ± 0.4	2.2 ± 0.3	1.5 ± 0.2
Non-Pensioners	9.9 ± 1.3	5.7 ± 0.9	4.2 ± 1.2
Pensioners' difference	62% less	61% less	64% less

Table 197: Hot water energy comparison

As shown, average standing losses were also much lower for the pensioners, at 1.5 kWh/day compared to 4.2 kWh per day for the non-pensioners. The lower standing loss for the pensioners was due to:

- smaller hot water systems (110 litres)
- the cylinders being inside the house
- all the systems being higher insulated, 'A' grade.

The cylinders in the non-pensioner houses were in general larger, older, poorer insulated and some in un-heated spaces - all contributing to higher standing losses. All cylinders in the pensioner houses were the same size, make, model, and age, and in identical locations, with the major differences in water storage temperatures. Table 198 summarises key information.

Hamilton HEEP households	Cylinder Age (years)	Cylinder Volume (litres)	Thermostat Setting (°C)	Tap Temp. (°C)	Estimated hot water use per day (litres)	% standing loss of total consumption
Pensioners	9.8	110.0	56.1	63.9	39.6	40%
Standard deviation	0.4	0	1.7	1.9	4.5	
Non-pensioners	15.1	147.0	64.5	62.1	101.0	35%
Standard deviation	3.1	7.5	2.5	2.1	16	
Pensioners difference		25% less	13% lower	Similar	61% less	

Table 198: Hot water systems – comparison of properties

Tap temperatures ranged from 57 to 76°C, with an average of 65°C. The thermostat settings for these systems averaged 56°C, with 55°C the most common. The settings were very misleading as one cylinder thermostat setting of 45°C delivered 73°C hot water at the tap.

For the non-pensioner houses, hot water systems varied greatly in types and operation. There were four gas systems, with two of these instantaneous types. Cylinder sizes ranged from 69 to 180 litres, grades from uninsulated to 'A' grade, and age from nearly new to over 45 years old. Tap temperatures ranged from 51 °C to 79 °C, and thermostat settings from 49 °C to 77 °C.

Standing loss determined by tap temperatures

Standing losses are determined by the physical characteristics of the hot water system, which in the pensioner houses were nearly identical. This gave a very good correlation between the standing losses and tap temperatures as shown in Figure 200.

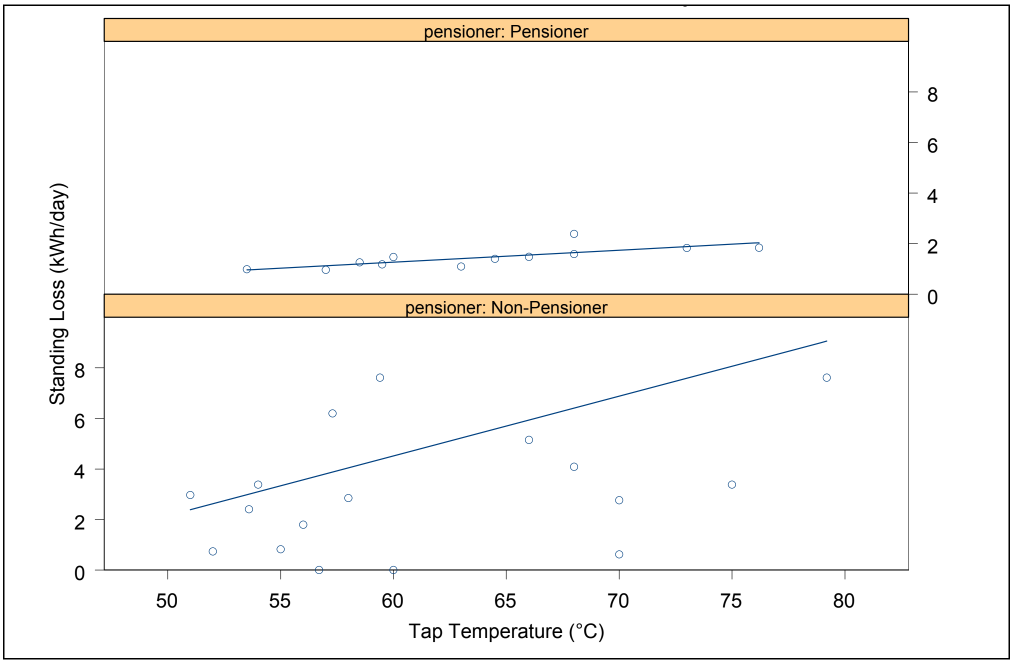

Figure 200: Standing losses as function of tap temperatures

Two anomalous houses were found, one where the hot water cylinder was turned off regularly to save energy, and the other where the occupants were awake at all hours of the day and night. In both these houses, special analysis had to be done to correctly estimate the standing losses.

From the linear model fitted to the pensioner standing loss data in Figure 200, it was possible to predict what standing losses would be if the tap temperature was set to 55°C. This should give a cylinder temperature of approx 60°C which is sufficient to control legionella bacteria in storage cylinders. The savings averaged $15 per year, simply from setting the thermostat properly. The estimated average daily hot water usage was about 39 litres per day, and no-one reported running out of hot water. It therefore appears that the cylinders are of sufficient size that reducing their temperature would not lead to inadequate hot water delivery.

If the pensioner houses had lower grade cylinders, standing losses would be much higher. With a 135 litre ‘C’ grade cylinder, the losses would be around $70 per year, and more than half the hot water energy consumption.

As the pensioners have a low hot water usage, careful sizing and specification of hot water systems is needed to ensure safe and efficient operation. The consequences of pensioners using large, low-grade cylinders could be a large increase in energy use from higher standing losses, and possible safety concerns if cylinder storage temperatures are manipulated to either save energy, or provide adequate shower performance from poorly designed systems.

Conclusions

The systems for the pensioners in this study are generally energy efficient, although the delivered hot water temperatures could be reduced in some cases in order to improve safety and efficiency.

APPENDIX 10: DHW STANDING LOSSES CALCULATION

Annual HEEP reports provided estimates of the standing losses of hot water systems, with detailed background on the calculation method provided in the Year 2 (Bishop et al. 1998), Year 7 (Isaacs et al. 2003) and Year 9 (Isaacs et al. 2005) reports.

The original method was based on selection of a time period with no hot water draw off to establish the standing losses but it was found that there were a large number of exceptional and unusual cases. A new method was introduced in the Year 7 report, and as a result the standing losses reported in the early HEEP reports have all been replaced by later estimates.

Initial standing loss estimation methods

The standing loss of a hot water cylinder is the energy used to maintain the water at the thermostat temperature when no draw-off occurs. During a long period where no hot water is drawn off, the element needs to switch on periodically to keep the water hot. Conceptually, the simplest method of estimating the hot water standing loss is to take data from overnight, when little or no water will be drawn off in most households. By looking at the average by time of day, the period of lowest consumption gives (in principle) a good estimate of the standing losses – see Figure 201, which was first used in the HEEP Year 2 report.

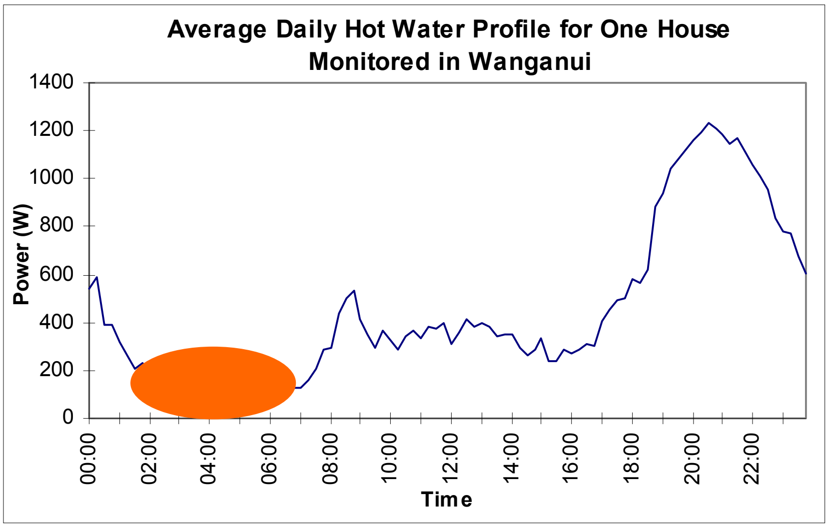

Figure 201: Average daily hot water energy use

Another method developed was to examine each individual recharge event. If standing loss recharge events are common, then the most commonly occurring recharge event in terms of the rate of energy loss will be associated with standing loss recharge. This was used when the first method failed for some reason.

Improved methods

Both of these methods are conceptually simple. However, many situations have been encountered where they do not give realistic estimates. Some of the problems are due to:

- ripple control
- households with unusual occupant schedules
- leaking systems
- solid fuel fired wetback booster systems or solar systems
- large thermostat dead-bands or cylinders that rarely recharge
- small elements that rarely switch off
- night rate tariffs.

The result of most of these is a big drop in the number of recharge events. Each of these problems will be discussed in detail, and the new analysis method introduced.

Ripple control

Ripple control is used to manage the network peak load during times of high demand and/or high electricity spot prices, by remotely turning off large numbers of hot-water cylinders. Typically, ripple control might be used during the morning or evening for a period of one or two hours, depending on the network demand. In some of the small towns and rural areas monitored in HEEP, ripple control was used much more intensively than in the cities, possibly in response to specific network constraints.

If ripple control is used only occasionally, and not always at the same time of day, then when the HEEP hot water data are averaged to a profile, the net effect is small and can be ignored. However, in many cases, ripple control was used extensively (e.g. Hamilton, Christchurch, and many of the clusters) putting a dip in the profile, which in turn can lead to an underestimation of the standing losses. Using a floating window of two or three hours can help, but can cause the standing losses to be evaluated during the ripple control period.

A fairly sophisticated method to remove long periods of ripple control was tested. This examined the time that a cylinder was off, and vetoed days when this occurred from being included in the analysis. This method fixed many of the problems, but unfortunately there was a large number of electric hot-water cylinders that had very long intervals between recharges, in many cases with intervals of between five and seven hours (see Figure 203). This routine could not distinguish these events, so to be effective required that times of ripple control be determined from examination of the monitored hot-water systems in that location.

Restricting the time of day during which the standing loss can be calculated is effective, providing the times to avoid are known. Unfortunately, ripple control regimes vary widely from location to location. An attempt was made to identify periods of ripple control by averaging the time series data for each region, and looking for extended periods when most or all of the electric hot water systems were turned off. This worked well for some, but not all, areas. In particular, areas where HEEP monitored a small number of houses (e.g. less than 10) gave ambiguous results.

Houses with unusual schedules

A number of households have unusual schedules, for example:

- bedtimes after midnight, with perhaps a shower taken before retiring
- rising early or shift workers; families with babies.

To get around this, a floating window approach was adopted, with the standing losses calculated from the lowest energy using three consecutive hours in the day for each household, whenever this might be. This approach avoided most difficulties. However, it did sometimes cause problems when ripple control was used during peak times in some regions.

Leaking systems

Some hot water systems leak, resulting in either very frequent energy recharges or periods of the element being on continuously. Such cylinders can often be identified by visual examination of the data. Normally the household will eventually identify the problem, either through noticing water in the house, total failure of the hot-water system, or unusually high power bills, so only rarely will a cylinder have leaked for the entire monitoring period. Vetoing days where the cylinder does not ever turn off deals with this problem if there is only a short period of leaking.

Two out of 171 houses showed clear evidence of continued leakage over a long period. Figure 202 shows 10 days of data for a cylinder that stayed on almost all the time for about three months, after which its behaviour went back to normal. The times when it turned off in this example were periods of ripple control. This leak would have cost the occupants about an extra $150 per month until it was repaired.

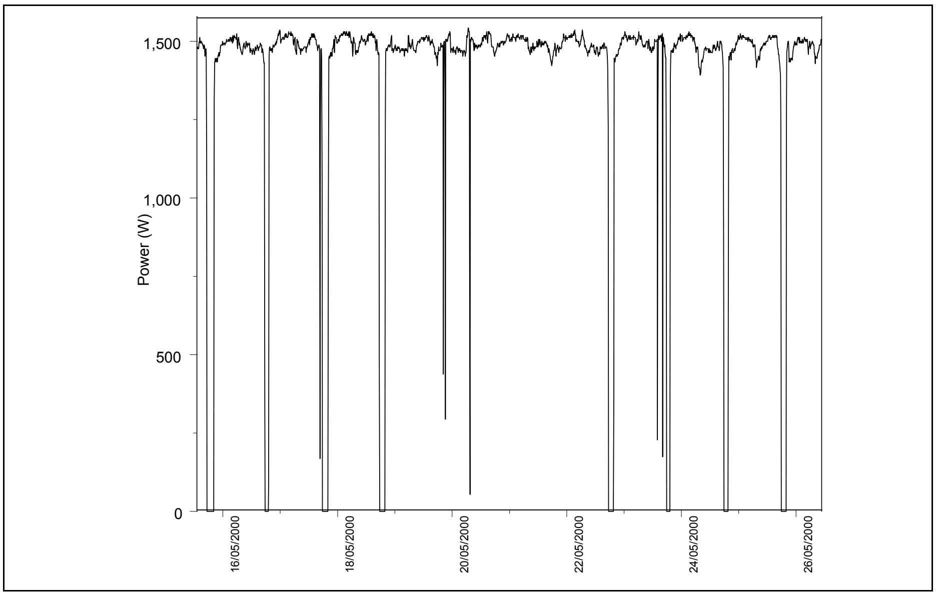

Figure 202: Leaking cylinder - only turns off during ripple control

Solid fuel wetback or solar

Wetback and solar water systems had only their gas or electricity consumption monitored directly. Most of the wetback and solar systems had additional temperature monitoring equipment installed. The inlet, outlet and internal temperatures were measured using thermocouples. When these data are analysed it should be possible to estimate the standing losses, and the energy contribution of solid fuel and solar energy for these systems. If that estimate cannot be performed properly, then the standing losses may not be able to be estimated.

Wetback systems are typically not active during summer, so taking data from summer periods only will normally allow standing losses to be calculated.

For solar systems, since the sun does not shine at night, standing losses can be calculated then, providing the daytime heating has not resulted in storage temperatures too far above the thermostat temperature.

Combined wetback and solar systems can be a problem, as many are deliberately operated to minimise electricity consumption, with some households permanently switching off the electricity supply. The only way, then, to calculate standing losses is to perform an energy balance based on the monitored temperatures. During periods of no wetback or solar input, and no water draw-off, the temperature will slowly drop in the cylinder, and standing losses can be calculated provided that the cylinder storage volume is known.

Two wetback systems in Hamilton used almost no electricity during the winter, as the wetback provided nearly all the required hot water. Standing loss calculations during these periods are impossible. To estimate the standing loss, any day that had zero energy consumption or on which the solid fuel burner was used for long periods were excluded.

Large thermostat hysteresis and/or infrequent recharge

On average, hot-water systems recharge about 10 times a day, or about every two to three hours. Many systems recharge much less often, with 25% recharging six or less times a day, and 7% less than three times a day. Figure 203 shows an example of a system that recharges only three times a day. The standing loss as calculated by the profile method was 0.7 kWh per day, but the usage during a holiday period was 1.7 kWh per day.

This behaviour may be caused by the thermostat having a large dead-band, so that the element only turns on once the cylinder has cooled by several degrees. Typically, recharge is triggered by an energy requirement of a few hundred Watt-hours, equal to a 1°C temperature drop for a 180 litre cylinder.

However, for many cylinders, the lowest recharge energy is larger, at 500 to 1000 Wh, corresponding to a thermostat dead-band of 3 to 5°C. Standing loss recharge is then only needed every four to eight hours, depending on the cylinder insulation. Often, water draw-off occurs more frequently than every eight hours, so the recharge is trigged by draw-off rather than by the standing loss. If the hot water is used late at night, there will be no recharge until the occupants draw-off water in the morning. This gives an apparently very low standing loss.

For these cylinders, there is no time of day that is predominantly standing loss recharge, nor are individual recharge events associated mainly with standing loss recharge. In these cases the only way to estimate the standing losses of is to find a number of days when there is no draw-off, for example, during a holiday period.

This problem is not confined to A and B grade cylinders, which might be expected given their low standing losses, as a lot of D grade cylinders exhibit the same behaviour.

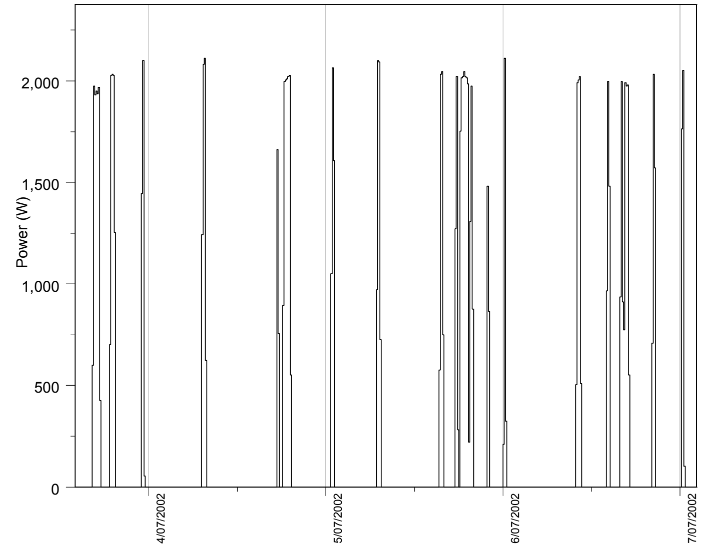

Figure 203: Cylinder that recharges occasionally

Small elements that rarely switch off

Hot-water systems that have elements of around 1 kW or less often spend large amounts of time on, simply because it takes about six hours for a 1 kW element to reheat a cold 135 litre cylinder. This slow recharge reduces the number of stand-alone standing loss recharge events that occur, and if hot water is used late at night, the cylinder can still be recharging well into the early hours of the morning, which leaves a small or non-existent window that can be ascribed to standing loss recharge. An example is given in Figure 204.

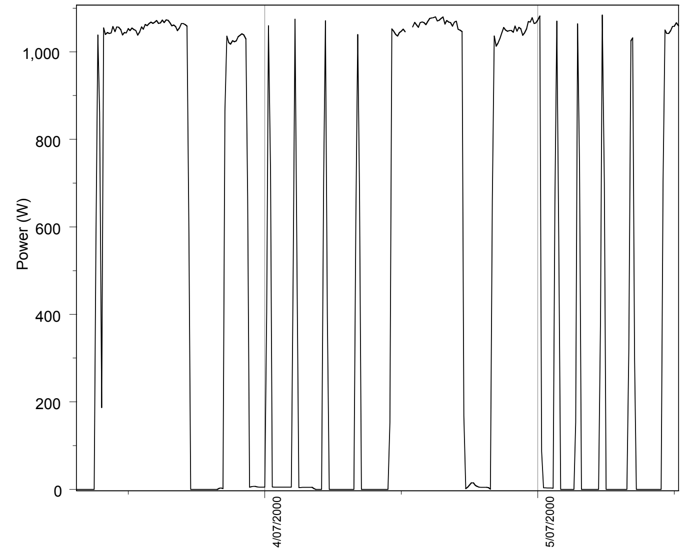

Figure 204: Cylinder that rarely turns off

Night-rate tariffs

Some systems are on a night-rate tariff, which supplies electricity between the hours of (typically) 11.00 p.m. – 7.00 a.m. A typical example of the energy use of these systems is given in Figure 205. Typically they have a very large recharge event at 11.00 p.m., lasting several hours, and then may have one or more recharge events before 7.00 a.m. If people use hot water before 7.00 a.m., there may be a draw-off recharge event.

The profile method does not work for these systems, as there are not enough hours overnight to avoid both the initial recharge, and any use at around 7.00 a.m. Taking the minimum usage over this period is likely to give a value that is too low, as the recharging is not randomly distributed in time. Taking the first peak after the recharge works for some systems, but many have low standing losses, and do not recharge for standing losses at all overnight. The large amount of energy used to recharge the cylinder is also a problem, as it can lead to significant temperature stratification in the cylinder. Subsequent recharge may be caused by mixing of the water, rather than a drop in temperature from standing losses.

In one cylinder that had a number of recharge events after the initial recharge, there was a systematic decrease in the energy of each recharge, indicating that the average temperature in the cylinder was increasing.

In general, estimating the standing losses of night-rate systems is difficult, and we do not have much confidence in the estimates. Two ways that might give reasonable results are:

1) take a number of days when there is no draw-off, for example during a holiday period, and assume the energy use equals the standing loss
2) examine the recharge peaks and assume that the smallest recharge peaks are standing loss recharge.

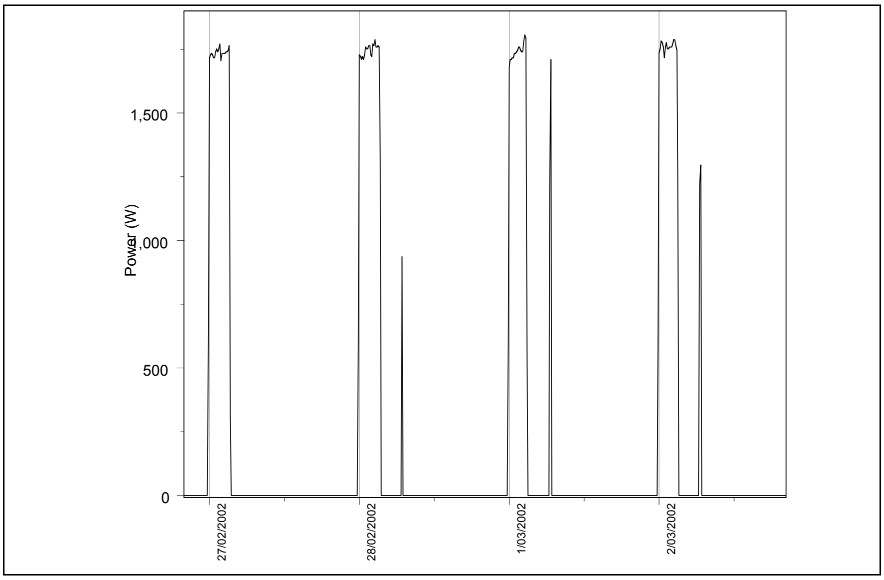

Figure 205: Night-rate hot water cylinder

Instantaneous hot water heaters

Gas or electric instantaneous hot water heaters are assumed to have no standing loss. They may have standby electric power consumption if they are electrically controlled, or the gas equivalent if operated by a pilot light.

Standing losses during periods of house vacancy

The new method for estimating standing losses is to visually inspect the data to find periods where the house is vacant. During these periods, the energy consumption of the hot-water system will be only to recharge standing losses. Typical examples of vacancy periods are given in Figure 206 and Figure 207, which use the total and hot water energy use as a selection mechanism. The only energy consumption seen in the total is from the hot water cylinder, and other equipment that is switched on permanently, such as refrigerators. The vacancy period is, on average, five days, though for about one-quarter of the systems a vacancy period of only two days or less was used. For some systems, it is not possible to find a period of vacancy.

As unoccupied periods are generally very short, the temperatures in the house during that time will not be typical of the whole year. For example, a Christmas holiday period would be likely to have average temperatures around 19 to 20°C, about 5 to 8°C above the yearly average temperature. The standing losses for this period will be lower than normal, and this will need some type of compensation. This compensation has not been undertaken for the estimates in this report – it is thought the difference will be between 5% and 10%.

Estimates of the average annual losses have been made, accounting for the cylinder temperatures and the environmental temperatures. However, this could not be done for all the hot water cylinders due to missing cylinder temperature or cylinder location data, reducing the number of cylinders with losses by 35%.

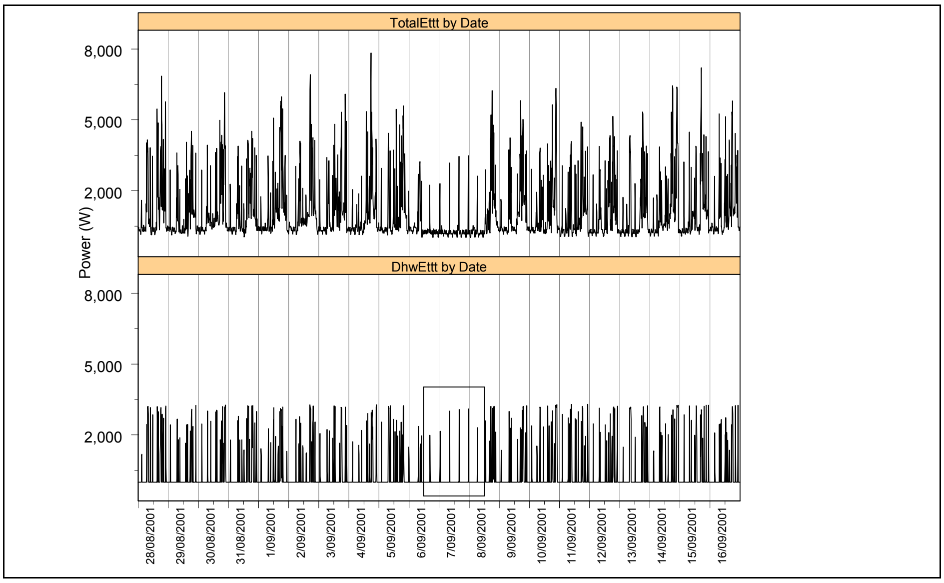

Figure 206: Example of a vacancy period

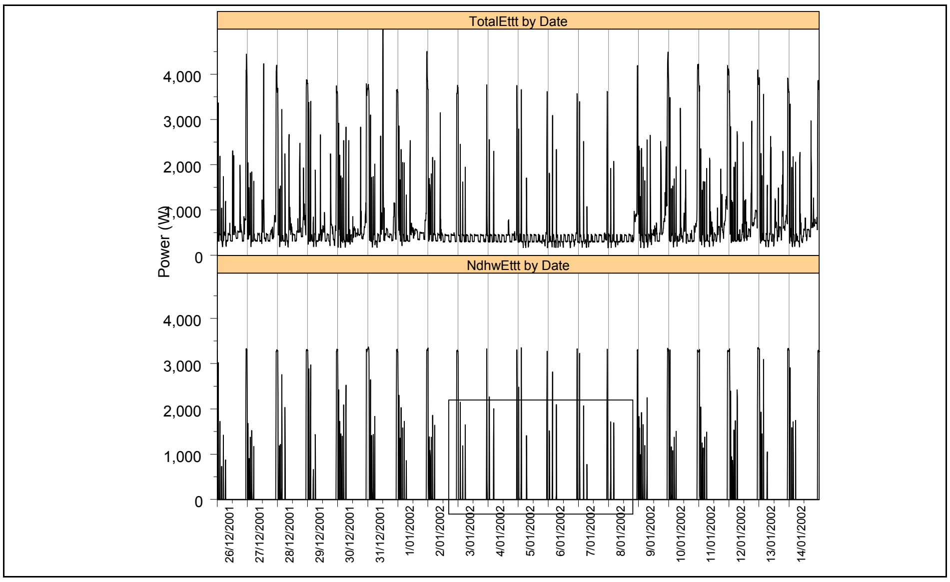

Figure 207: Example of a vacancy period for a 'Night rate' hot water system

APPENDIX 11: DHW WET-BACK (SUPPLEMENTARY) WATER HEATING

This work was originally reported in the HEEP Year 9 report (Isaacs et al. 2005).

Introduction

In addition to the direct use of purchased fuels for the production of heated water, many New Zealand homes make use of a 'wet-back'. The wet-back takes heat from a solid fuel burner (the rest being used to heat the house or cook food) and stores the heated water in a hot water cylinder – normally the main household cylinder, but in some cases a dedicated cylinder.

Wet-back water heating monitoring was first implemented in HEEP in 1999, initially on a trial basis, and then as part of full-scale monitoring. Prior to 1999 there were only three wet-back systems in the monitored houses. This section briefly describes the monitoring regime, but does not attempt to describe the many false starts, dead-ends and changes to the methodology.

Wet-back heating systems were monitored by measuring the temperature of the cold inlet, and either the cylinder wall temperature or the hot water outlet pipe temperature. It was found to be impractical to monitor water flows. In the end, it was found that monitoring either the hot outlet or the cylinder wall temperature alone was sufficient to allow estimation of the wet-back energy inputs, in conjunction with heat output estimates from the solid fuel burner.

Calibration of wet-back systems

The final calibration of the wet-back systems commenced after the successful calibration of the solid fuel burner heat outputs. The method establishes a correlation between the rate of increase of cylinder temperature which, assuming no water draw-off, is directly proportional to the energy input, and the solid fuel heat input.

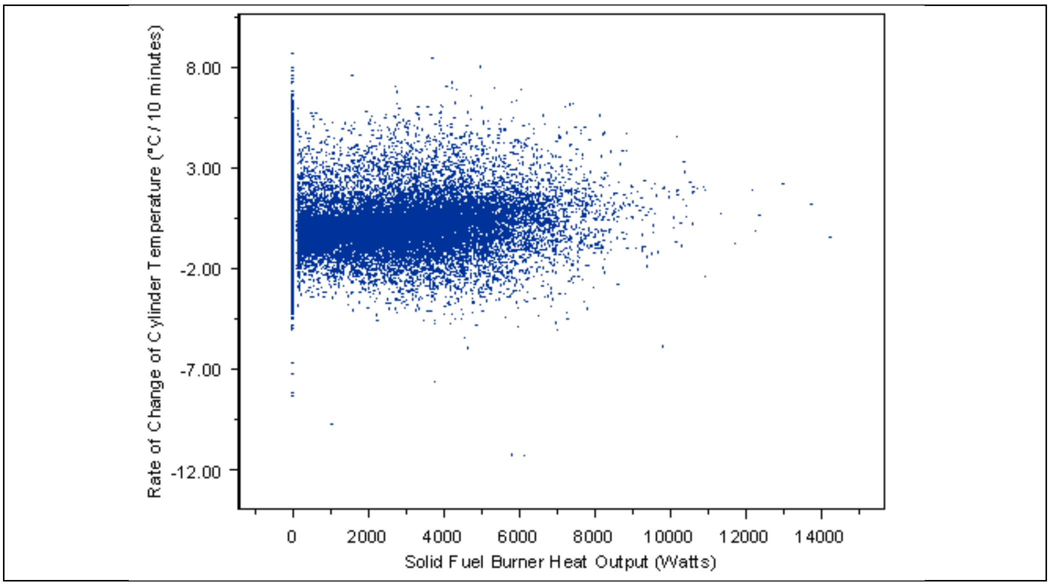

Figure 208: **Solid fuel burner output vs. rate of change of cylinder temperature**

An example of the data at 10 minute intervals is given in Figure 208. Where there is a correlation between the two there is also a lot of scatter. To reliably fit a linear model to this data, the data were aggregated by solid fuel burner input into 100 W bins, as illustrated in

Figure 209. Note that in Figure 209 the number of data points averaged in each 100 W interval varies, and at the higher end, there are very few points. When a weighted linear regression line was fitted to Figure 209 it had a slope of 0.0001038, which when rescaled from rate of temperature change per Watt of solid fuel heat input to change in energy per Watt of solid fuel heat input gives 0.125 W/W. So for this wet-back connection, for every Watt of heat output of the solid fuel burner for space heating, 0.125 W goes into the hot water cylinder.

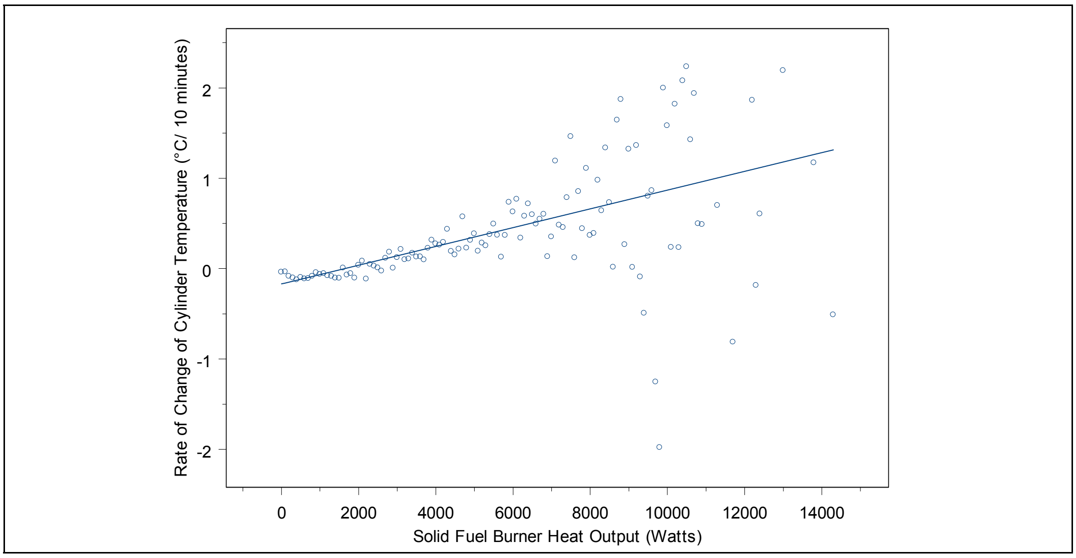

Figure 209: Solid fuel burner output vs. rate of change of cylinder temperature

The method used gives the slope of the relationship, but the intercept is not meaningful. Since the fitted line slope is insensitive to the addition or subtraction of a constant, the standing losses of the hot water cylinder are not accounted for. To account for them, a power equal to the standing losses is added when the wet-back connection is actively supplying energy to the hot water cylinder.

Figure 210 shows the combined electric and wet-back hot water energy used by one system for a whole year. The electricity was turned off between about April and November for this house, and the wet-back was the sole source of energy for hot water over that period. This can be seen in the sudden change in the pattern in the top panel, which is 10 minute data. In the lower panel, the upper line is the weekly moving average of the combined wet-back and electricity energy consumption – this energy consumption is fairly consistent between the summer months and the winter months, when the wet-back is the sole heating source.

This is a good indication that the calculation of this wet-back energy is correct, as the energy consumption is driven by the demand of the household for hot water. For this house, the annual hot water energy consumption was about 2,400 kWh, with about 900 kWh from electricity and about 1,500 kWh from the wet-back.

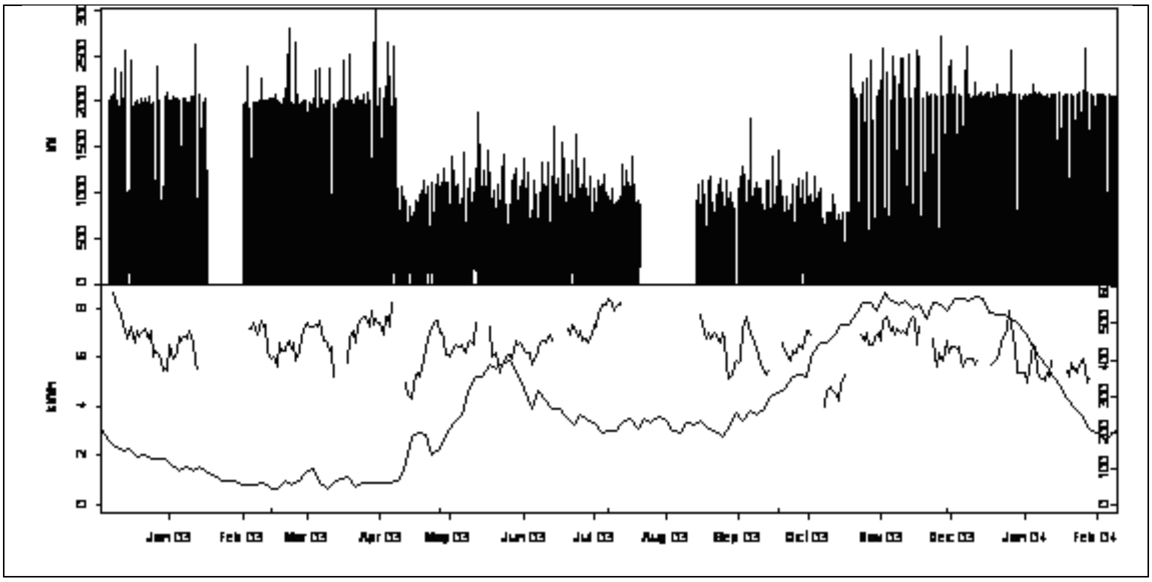

Figure 210: Combined electric and wet-back water heating energy

A number of other wet-back systems were tested to trial the method. Generally, the method as described works well. In some cases where there was a lot of hot water drawn off during periods when the wet-back connection was operating, the method failed, as the rapid draw-off is equivalent to an energy output of 10-30 kW for the hot water system, and the water temperature drops rapidly. This destroys any positive correlation between the rate of change of water temperature and solid fuel heat input. In these cases, a subset of data was taken when the electricity consumption was zero, and when the rate of change of temperature was positive.

In other cases, this method was not sufficient to deal with water draw-off, and a different subset was taken when the water temperature was above the low point of the thermostat deadband. Effectively, this only takes those instances where the hot water cylinder is being overheated to some extent by the wet-back connection. This helped in some other cases.

The overriding advantage of this calibration method is that it establishes the wet-back energy input as a fraction of the solid fuel heat input. The calibration of the wet-back system itself requires only a small amount of data – often only a few days is enough. As the monitoring of the hot water cylinder and wet-back connection and solid fuel burner involves at least two data loggers (for electricity and thermocouple temperatures) and at least three thermocouples, the chances of any one channel of data being invalid due to logger or wiring faults or loose wires is increased. Once the calibration factor is determined, the wet-back energy data is calculated from only one monitored logger channel: the solid fuel burner. Using a continuous heat balance of the hot water cylinder would generate many more missing data.

The fraction of the solid fuel heat input that goes to the wet-back varies considerably between systems. The amount of energy that is transferred to the water depends on the temperature of the firebox and the layout of the wetback itself. Typically a wet-back connection to an enclosed wood burner has an output 5-10% of the solid fuel burner heat output. For dedicated chip heaters, the fraction is greater mainly due to the very low space heating output of these types of burners (they have a water jacket around the combustion chamber so most of the heat goes into the water and not the room).

The analysis presented in Table 199 gives the wetback heat output to the hot water cylinder as a percentage of the gross energy input to the burner, for the different types of wetbacks found in the HEEP sample. Note that the relatively small counts apart from solid fuel burners.

The values in Table 199 are used as follows: e.g. for every 1 kW of wood put into a solid fuel burner, there is 0.16 kW heat output to the hot water cylinder, while the remaining 0.84 kW is split between the heat released into the room, the hot flue gas sent up the chimney or incomplete combustion (soot).

Wetback type	Wetback heat output as % of gross heat input	SE	HEEP Count
Open fire	5%	-	1
Pot belly stove	14%	9%	2
Wood range	38%	21%	5
Solid fuel burner	16%	4%	50
Chip heater	46%	22%	5

Table 199: Wetback heat output percentages