Retrofit alternatives for State Houses in Cold Regions of New Zealand

REPORT Nº 2

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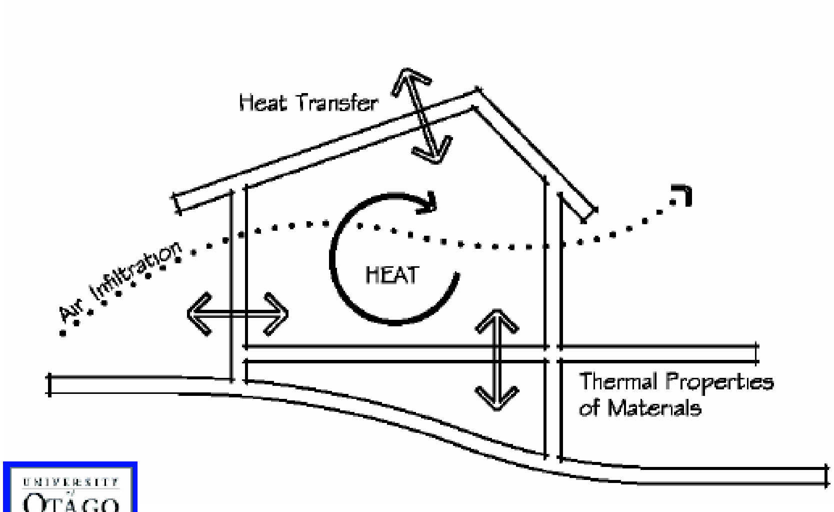

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EXECUTIVE SUMMARY

This report details the findings of the second stage of our 5 year housing research project sponsored by the Foundation for Research Science and Technology (FRST). The research has consisted of monitoring the efficacy of the 'Housing New Zealand Corporation's Energy Efficiency Retrofit Programme' implemented by Housing New Zealand Corporation (HNZC) in state houses across NZ and exploring alternatives to further improve the comfort and efficiency of these houses.

Findings of the first stage suggested that: only a small increase of around 0.4ºC in annual average indoor temperatures (0.6ºC average over the winter months) and a decrease in electrical energy consumption of around between 5% and 9% were observed after the HNZC upgrade package. Occupants were found to be exposed to absolute indoor temperatures considerably below the WHO recommended minimum of 16°C with average indoor temperatures of 14.9°C in living areas and 13.4°C in bedrooms (for Dunedin). Alarmingly occupants could be exposed to indoor temperatures of less than 12°C, for nearly half (48%) of a 24 hour day during winter months (June to August). Also, the minimum temperature (averaged over the sample) recorded in those months was between 5°C and 5.4°C with little improvement after the upgrade, providing a health risk for its occupants. It was also noted that typical occupants provide relatively little energy for space heating and that they do not usually heat the entire house. Excluding energy to heat water, occupants used an average of 5600 kWh of net energy a year.

If improving indoor thermal comfort and at the same time making energy efficiency at homes were the goal, then more intensive housing insulation measures or better home energy efficiency technologies would need to be applied. Therefore our study suggested that a program to look at other options was needed if existing conditions were to be improved. Thus the second stage of our research has been exploring some of these options to improve the energy efficiency and thermal comfort of state houses in NZ.

Introduction

This study highlights the importance of improving the energy efficiency of the existing housing stock in NZ and explores ways of investing in energy efficiency improvements by upgrading the building fabric performance to a greater extent than that undertaken in the basic HNZC energy efficient upgrade program and by exploring the impact of different heating appliance options.

Upgrading the existing stock will provide benefits at different levels: Social cost and benefits by improving the quality of life through reducing health risks and seasonal mortality. Private cost and benefits by providing a healthier environment to achieve thermal comfort at home will have an impact in the way people live and use their homes. Environmental cost and benefits by reducing the levels of CO_2 emissions over the years is crucial if the consequences of climate change are to be minimized.

The energy efficiency and indoor comfort of existing housing can be raised by: improving the building fabric performance, improving the heating system efficiency (including the control system), increasing the amount of potential solar gains into the house, (openings and configuration improvements), using high efficiency appliances and educating occupants on optimal behaviour.

It has been widely recognized that cold and damp houses can have a negative effect on the health of occupants. Previous studies by the Wellington School of Medicine, among others, have recognized the importance of insulating houses which can have an effect in terms of health improvements.

Methodology

In stage two of our FRST funded study we implemented different insulation options as retrofits to two state houses in Dunedin; we used a technique of whole house calorimetery to measure the actual improvements in the thermal resistance of the building fabric, and simultaneously modelled the houses to determine the differences between this approach and experiment. We then used the experimental results with a modelling program to calculate the annual heating requirements for various heating schedules. Finally we proceeded to undertake an analysis to help choose the most cost effective upgrade path from a

selection of heat loss reduction retrofits and heating system upgrades.

In order to measure the thermal performance of both houses, we used the whole house calorimetry. This method is very similar to a published method referred to as a "co heating test" and is a method of determining the actual heat loss due to combined fabric and infiltration losses of unoccupied dwellings. The method works by measuring the heating power required to maintain a constant temperature difference between the interior and exterior of the building under near steady-state conditions.

We then proceeded to estimate the annual heating requirements for both houses using a computer modelling package developed by the Building Research Association of NZ (BRANZ) called ALF3.

The impact of various heating system upgrades were considered. New efficiencies were modelled as either increasing comfort or reducing fuel cost and associated carbon emissions.

Finally we estimated outcomes of a combination of upgrade options undertaking a cost benefit analysis. Possible upgrade options have been compared and ranked. To do this, the value of energy saved over a set time frame has been compared with initial cost of investment.

The houses

Two houses, located in Brockville, Dunedin, were retrofitted to identify improvements to reduce heat loss through the building envelope. The state houses were built by HNZC during the 1960s. One had concrete block walls and a tiled roof and had been upgraded with the recent HNZC upgrade package of polyester ceiling batts and underfloor foil, while the other had a combination of brick and weatherboard cladding and had not been recently upgraded.

The new upgrades included installing different types of insulation to all exterior walls, fitting double glazed windows, floor and ceiling insulation of one house and concentrating on the living room of the second house.

In addition to the thermal experiments several practical observations came out of the upgrade process. For instance it was difficult to get contractors to undertake the work. It was found that retrofitting the existing window frames to install double glazing was more expensive than purchasing new ones. Purchasing drapes and pelmets was found to be considerably more expensive than expected. Retrofitting the walls by adding a layer of expanded polystyrene and then GIB, was not as easy as initially thought. Installing a reflective foil/bubble wrap product called 'Air Cell' under the floor was easier than installing normal reflective foil. Removing vinyl and carpet was not easy in some areas and remedial work to the floor (including sealing) required considerable extra contracting time to be spent. One reason for the latter problem was that our heating test caused moisture removal, which unfortunately caused the wooden floor to shrink, leaving gaps which had then to be filled. Blower door tests were useful to identify areas of high air infiltration including corners (especially inside wardrobes and along cornices and skirting), also some (but not all) of the wooden framed windows were found to be very leaky. Some of the acrylic sheets that were attached using magnetic strips to existing window panes did not perform as expected, causing air infiltration between the acrylic and the windows which in turn caused condensation in the air gap.

An open day for both houses participating in a local event offered a chance for the community to visit the houses and make contact with the retrofit process and the people involved in the project. Many visitors interested in retrofitting their own house asked questions regarding the performance and practicality of each upgrade option. From that event it was evident that there is a need in this area to provide advice on how to achieve warmth in existing houses.

Results

Expected Thermal performance

Both houses were identified to have an original R value of between 0.40 m^2K/W and 0.41 m^2K/W (when originally built). After reducing heat losses through different upgrades, a gradual increase in the thermal resistance of the building fabric was expected for both houses. After fully insulating House 1, a final effective R value of 1.11 m^2K/W was expected. House 2 was expected to achieve an effective R value of 0.91 m^2K/W in the living room only. This represents a factor of 2.7 improvement for House 1 and 2.2 for House 2 from the originally non insulated house.

However because some of the insulation had been installed in previous upgrades the improvement expected from our first to final test was of a factor of 1.7 for House 1 and of 1.8 for House 2.

Monitoring Results

House 1 The total heat loss of the original house was 438±80 W/K. The use of drapes reduced the heat loss to 409±41W/K. Removing the underfloor insulation and carpet increased heat loss, in part because of the increase in air leakage measured. Adding EPS underfloor insulation restored the heat loss to a value similar to the original heat loss. Double glazing reduced the heat loss yet further. The most significant heat loss was achieved by insulating the walls. Final R value for this house was **0.99 m²K/W** for the whole house including drapes and 0.83 m²K/W without drapes.

House 2 The total heat loss of the original living room of House 2 was 164±7 W/K. Insulation upgrades reduced this to 84±8 W/K, with the most significant steps being the addition of drapes, and insulation of the walls. The use of drapes or window plastic after insulation further reduced heat loss to a identical (statistically significant) 70±5 W/K. Final R value for the living room of this house was **1.02 m²K/W** for the living room including drapes and 0.90 m²K/W without drapes.

The changing environmental conditions meant that the accuracy of this test method has not allowed a statistically significant comparison of R values at each level of construction but the final results for the R values are statically significant.

Within the margin of error, the heat loss of the original house (H1-1) was within that predicted by theory. However the performance of the floor insulation may be less than that calculated using the given R values for the material. The heat loss expected when the carpet and underfloor insulation was removed was much less than expected. The difference cannot be explained by experimental uncertainties alone.

Monitored improvements differed from those calculated. The differences were less than 20%. This was thought to be due to uncertainties in thermal bridging, an increase in air infiltration after re-gibbing, and lower than expected R values due to gaps between the structure and the insulation.

It is anticipated that further improvements, thicker insulation, quality control during the upgrade process and substantial decrease in air infiltration facilitated with blower door use during retrofits could further reduce heat losses by 25 to 50% for the whole house.

Annual Heating requirements

According to our modelling, similar energy is required to heat the whole house for evening schedule before the upgrade as it is to heat the same house for the whole day after the house was fully upgraded, to the same temperature.

Also, after the upgrades, the same energy is required to heat the living room for 24 hours to 20ºC than it is to heat the whole house during evening only to the same temperature.

Before the improved upgrade, heating the house during the evening to 18ºC required 3800 kWh per annum while after the house was fully upgraded the requirement was reduced to 1600 kWh. This reduction means around 66% savings in net heating energy requirements for the evening schedule (see chapter 4 for details).

Cost Benefit Analysis

Our cost benefit analysis examined the direct financial impact of various upgrades to reduce heat loss and switch to the use of renewable, efficient heating. We calculate the carbon emissions associated with producing and using building retrofits.

When initial retrofit costs are offset by future discounted heating cost savings, many upgrades are economically neutral in less than 10 years. Some retrofit options do not pay off in 10 years, when considering only the benefits of reduced energy. The value of the energy benefits mean the real cost of the upgrade is likely much less than the many other non-monetary benefits, such as increased health, satisfaction, and others.

The financial benefits of energy saving upgrades are reaped by the tenants, even though HNZC pays the costs. We may then prefer to look at the efficacy of expenditures on heating costs or comfort gains. We have enough information to predict upgrades costs, and their effects towards reducing recurrent heating energy, fuel cost, and CO_2 emissions. The cost benefit analysis shows how to reduce these in the most effective way, that is, with the least incremental cost per incremental improvement to energy savings. These types of analysis will help Housing New Zealand respond to Govt[3] initiatives.

Conclusions and Recommendations

The original HNZC upgrade was simple to implement and reasonably cheap to fund, going the next step will be more difficult and more expensive.

Each upgrade step will incur significant financial costs but can lead to reductions in CO_2 emissions and energy consumption plus an increase in thermal comfort. Funding the costs will be a challenge but a challenge that will have a payoff over the long term.

Going the next step in terms of building fabric upgrade includes installing wall insulation and in the longer term double glazing. The improvement to the thermal properties should then be sufficient to bring the housing stock up to that required by the current building code or better.

Improving building fabric by reducing heat losses alone will not provide WHO recommended indoor temperatures and providing a path for efficient space heating at a cost commensurate with the circumstances and the income of the occupants of state housing needs to be attended to. Heat pumps are suggested as a particularly efficient source of space heating when they replace other electrically driven heating.

Further analysis to quantify the benefits of zoned heating and passive solar retrofits, including conservatories is required. These retrofits were not ranked as part of our study. There is still much potential for well designed conservatories and other passive mechanisms to reduce heating loads for adjacent rooms.

In addition replacement of low efficiency wood burners with newer, cleaner wood burners or pellet fires is desirable. Replacing solid fuel burners with heat pumps is not recommended unless in areas affected by air pollution, as this new electricity demand will lead to electrical capacity problems and higher carbon emissions for New Zealand.

We support the efficient practice of zoned heating. In some houses insulating one room completely may be appropriate. The zoning should allow for WHO recommended temperatures in the living room(s) (18-22°C), and at least the maintenance of minimum temperatures in the rest of the house(>16°C), possibly via a combination of solid fuel heating in the lounge and heat pump heating for the hall and bedrooms.

Importantly, information should be provided to tenants on how to realise energy efficient healthy housing from an occupants point of view.

Information packs could be provided to all HNZC tenants on how to manage the indoor environment and provide the health and comfort for all age groups. Such packs could also include information of carbon emissions and the value of using energy efficient appliances, curtains and space heating.

According to our analysis, upgrades to reduce heat loss, in order of efficacy, should be:

- Insulate the ceiling (Completed)
- Insulate the floor (Completed)
- Install a low emissions wood burner or pellet fire (if not done yet)
- Install a heat pump if it will replace electric heaters used elsewhere in the house.
- Improve air-tightness
- Insulate walls
- Install double glazing and/or drapes

Table of Contents

Index

Chapter 1 INTRODUCTION

Chapter 2 METHODOLOGY

Chapter 3 HOUSES DESCRIPTION

Chapter 4: RESULTS

Chapter 5: Cost Benefit Analysis

Chapter 6 CONCLUSIONS AND RECOMMENDATIONS

Appendix

References

List of Figures

List of Tables

Abbreviations

ALF3	Annual Loss Factor (Version 3)
24HR	24 hours Heating Schedule
ACH	Air changes per hour
ALL	All day Heating Schedule
BRANZ	Building Research Association of New Zealand
CBA	Cost Benefit Analysis
ºC	Degree Celsius
DBH	Department of Building and Housing
EECA	Energy Efficiency and Conservation Authority
EVE	Evening Heating Schedule
FRST	Foundation for Research, Science and Technology, New Zealand
GIB	Gypsum plasterboard
H1	House 1
H2	House 2
HDD	Heating Degree Days
HEEP	Housing Energy End-use Project
HNZC	Housing New Zealand Corporation
HL	Heat Losses
K	Kelvin
kWh	Kilowatt per hour
LCA	Life Cycle Analysis
m^2	Meter square
ME	Morning and Evening Heating Schedule
MED	Ministry of Economic Development
MfE	Ministry for the Environment
NIWA	National Institute of Water and Atmospheric Research
NTD	Net Temperature Difference
NZ	New Zealand
NZBC	New Zealand Building Code
NZS	New Zealand Standards
OECE	Organization for Economic Co-operation and Development
Rv	R values
STEM	Short Term Energy Monitoring
UK	United Kingdom
W	Watt
WF	Warm Front
WHO	World Health Organization

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CHAPTER 1 : INTRODUCTION

1.1 Introduction

This report details the findings of the second stage of our 5 year housing research project sponsored by the Foundation for Research Science and Technology (FRST) and undertaken by Energy Management (Department of Physics) at the University of Otago. The research has consisted of monitoring the efficacy of Housing New Zealand Corporation's (HNZC) energy efficiency retrofit programme' implemented in state houses across NZ. The report documenting the findings of the first stage was finalised in 2006 [1].

Previous studies have suggested that houses in NZ are often cold and damp [2][3][4]. Because a large proportion of NZ homes were built before energy efficiency regulations came into force in 1978/79 many of the older houses are very difficult to heat economically. This situation is particularly true for housing occupied by low income people living in the colder regions of the country. It has been shown that unhealthy indoor conditions predominate in such housing with very low indoor temperatures during winter months [5] [3].

The HNZC energy efficiency upgrade programme was initiated to improve the existing situation with regards to pre 1978 state houses across the country over a 7 year period. The programme commenced in 2001 and included installing bulk insulation in the attic space, reflective insulation under the floor, and draught stopping under the doors.

Unfortunately, findings of our stage one report suggested that the programme has provided little improvement in terms of raising the minimum indoor temperatures towards those accepted by the WHO [6] for a healthy indoor environment, particularly in the cooler parts of the country. After a two year monitoring period, our study suggested that a programme to look at other options was needed if existing indoor conditions were to be improved. The second stage of our research has been exploring such options to improve the energy efficiency and thermal comfort of state houses in NZ.

1.2 Warm houses for health and wellbeing

1.2.1 Importance of improving the energy efficiency of the existing housing stock in NZ

Because little has been done over the past years to substantially improve the situation with regards to old thermally inefficient houses in NZ and because these houses account for such a large percentage of residential homes in NZ [7], there is some urgency to explore retrofit options. Upgrading the existing stock will provide benefits at different levels:

- *Social costs and benefits*: reducing fuel poverty and its consequences will have an impact in improving the quality of life through reducing health risks and seasonal mortality.
- *Private costs and benefits*: providing a healthier environment to achieve thermal comfort at home will have an impact in the way people live and use their homes. People will benefit more from the same amount of energy.
- *Environmental costs and benefits:* CO_2 emissions which result from burning fossil fuels are a major cause of concern[8]. Reducing the levels of CO_2 emissions over the years is crucial if the consequences of climate change are to be minimised.

1.2.2 Exploring ways to improve the energy efficiency of the existing housing stock in NZ

Upgrade of the existing housing stock can be accomplished by implementing energy efficiency measures. The energy efficiency of existing housing can be raised by:

- Improving the building fabric performance,
- Improving the heating system efficiency (including the control system),
- Increasing the solar gains into the house (openings and configuration improvements),
- Using high efficiency appliances,
- Support zoned heating, and
- Educating occupants on optimal behaviour for energy efficiency.

The optimum energy efficiency (for a given cost) for specific residential houses would be accomplished using some combination of the above factors, depending on the specific conditions and circumstances.

For houses not designed adequately in terms of passive solar collection, insulation alone will not generally provide a healthy indoor environment without adequate space heating. Since reducing non-renewable energy is also a goal, it is thought that considering renewable space heating options including optimising available solar energy is a necessary part of housing upgrades.

Many factors influence the way people balance the cost of heating and comfort choices. These factors include (among others) the available funds to spend on space heating, the schedule and set point temperature established by each householder and the size of the heated area (heating only one room vs. heating the whole house). Air infiltration rates and behaviour, that is how people manage the indoor areas, such as opening windows and doors, will also have an effect.

1.3 Aim and objectives of this report

This report presents the results of our investigation that has explored ways to improve the energy efficiency of existing state houses in southern NZ, beyond that provided by the standard HNZC upgrade programme. The aim being to provide an indoor environment that could lead to warm houses without necessarily increasing purchased energy consumption or increasing carbon emissions.

The main aim has been to explore energy efficiency improvements by upgrading the building fabric to a greater extent than that undertaken by the basic HNZC energy efficiency upgrade programme and in addition to explore the impact of different heating appliance options.

To achieve this aim the following specific objectives were undertaken:

- Investigating two state houses, located in Brockville, Dunedin, which were retrofitted with a combination of materials and components in order to identify specific improvements in the thermal performance of the building envelope at the component level.
- Using computer modelling on the above houses to investigate ways of varying insulation levels, fuels, heating appliances, and heating options for residents.
- Exploring the impact of different heating systems, set point temperatures, heating schedules, and heated areas. This aim analysed the effect that each one of these variables had in energy consumption and occupants' thermal comfort.

1.4 NZ situation and housing trends

1.4.1 Climate in NZ

New Zealand has a cool temperate climate, lying between 34 and 46 degrees south. The South Island is significantly cooler than the North Island with Dunedin in the south having some 2580 heating degree days (base of 18^{o}C) compared to Auckland in the north which has 1150 heating degree days (base of 18^{o}C).

The mean annual temperatures in NZ range from 10°C in the south to 16°C in the north. Southern NZ has cool coastal breezes and winters are cold with infrequent snowfall but frequent frost. Typical winter daytime maximum air temperatures range from 5°C to 12°C. Hours of bright sunshine average about 1600 hours annually and are often affected by low coastal cloud [9].

1.4.2 Energy use in NZ

Energy use in the residential sector in NZ accounts for around 13% of the total consumer energy used in the country every year [10]. This percentage does not include the significant portion of land and air transport energy use by the inhabitants of the residential sector. Space heating accounts for around 34% of the total household energy use in the country. This is followed by 29% for water heating with the remainder for lighting, refrigeration, and other appliances[3]. Even though the cost of energy in NZ is lower than most OECD countries[10], New Zealand's domestic energy consumption is low compared to other OECD countries with similar climates[11]. It is likely, however, that low energy costs have contributed to the lack of emphasis on building energy efficient housing. The low use of purchased energy for domestic heating on the other hand is advantageously in the light of a fuel and carbon constrained world. The question is how to be more comfortable while using this lower quantity of purchased energy?

In addition, considerable energy is spent every year in the building industry in constructing new houses, retrofitting existing ones, and undertaking maintenance work. Construction of residential houses makes up almost 2/3 of the building and construction industry energy usage[12].

1.4.3 Regulations and incentives

Since 1977 methods for controlling heat losses in the residential sector in NZ have been gradually introduced for all new houses, namely requirements for insulation [13][14][15]. The building code was revised in 1996, dividing the country into 3 zones and with different requirements for solid and lightweight construction. A second revision was completed in 2004 as shown fig. 1. There are currently (June 2007) no requirements for window thermal performance other than that accessed by the calculation method to form compliance with the code. The building code is currently being revised and it is likely that double glazing will be a requirement for colder areas in the near future.

In terms of air leakage, the building code does not regulate the maximum amount of heat losses occurred by air infiltration. In order to guarantee the quality of air in new houses, it limits the net openable area of windows or other openings to be no less than 5% of the floor area[16].

No insulation is required for houses constructed before the code came into force. However, there have been some incentives to retrofit existing houses which have mainly focused on insulating the ceiling and floor. Not much effort has been given on how to reduce heat losses through windows or other parts of the building fabric.

In general buildings built before 1972 will not have been insulated (ceiling insulation became mandatory around this date in Christchurch, before 1978 national regulations) and houses built before 1960 may be more likely to suffer from more leakage and draughts [17].

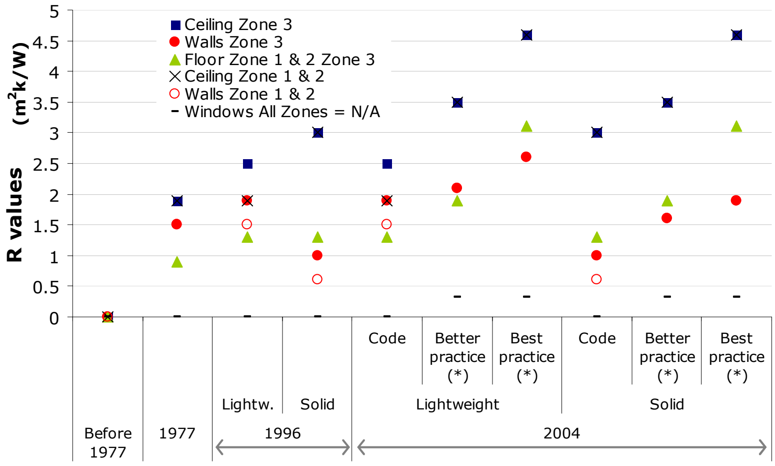


Figure 1. Building Code regulation and recommendations for insulation in NZ

1.4.4 State houses and relevant previous studies

State houses in NZ were originally built to a relatively high standard in terms of materials and workmanship, but because most of them were built before the national energy efficiency regulations came into force in 1979, they are very difficult to heat. Today these houses provide an affordable option for low income people. The fact that this group does not own their accommodation provides little incentive for them to invest in energy efficiency upgrades that do not have a payback time under their perceived occupancy period. In addition, such groups will have fewer resources to invest in such options and they are most likely to be living with energy costs that are a large fraction of their income.

The financial inability to heat the home to an adequate temperature results in thermal discomfort and health risks, a condition which has been defined in the UK as fuel poverty[18] [19]. A study on "Poverty and Comfort" by BRANZ suggested that "energy is a significant cost item for low income households" in NZ and that "our houses are not achieving conditions which promote or even support good health" [20]. A more recent study suggested that between 10% and 14% of the population of New Zealand is currently living under fuel poverty conditions, with the percentage in the lower South Island being much higher [21].

The findings of the HEEP study by BRANZ monitoring over 400 houses across NZ found that the country-wide average winter evening living room temperature was 17.9ºC. Their findings also suggested that post 1978 houses were on average 1ºC warmer than pre 1978 (for winter evening temperatures recorded in living areas). They also found that only 5% of NZ houses have central heating systems and houses heated with solid fuel burners are warmer than others.

As mentioned before, findings included in our previous report suggest that the upgrade programme had little substantial impact in improving existing conditions in pre 1978 houses in the southern parts of NZ. A summary of the findings from this report include:

- A small increase of around 0.4ºC in annual average indoor temperatures (0.6ºC average over the winter months) and a decrease in electrical energy consumption of between 5% and 9% were observed after the HNZC upgrade package.
- Occupants were found to be exposed to absolute indoor temperatures considerably below the WHO recommended minimum of 16°C with average indoor temperatures of 14.9°C in living areas and 13.4°C in bedrooms (for Dunedin), providing a health risk for its occupants. Alarmingly, occupants could be exposed to indoor temperatures of less than 12°C, for nearly half (48%) of a 24 hour day during the three winter months of June, July and August.
- The minimum temperature (averaged over the entire sample) recorded during winter months was between 5°C and 5.4°C with little improvement after the upgrade.
- It was also noted that people provide very little energy for space heating and that they do not intend to heat the entire house.
- Improving insulation at the levels applied did not significantly improve indoor temperatures in Southland to levels that would be considered healthy (no real improvement in absolute indoor temperatures since at least 1972).
- These results together with the thermal modelling suggested that if no indoor temperature increase was achieved after the upgrade, then a reduction of between 6% and 10% in total energy consumption could be expected. The maximum savings would equate to a simple pay back time of 10 years (and save 160 kg of CO_2 per year).
- The reasons for this small improvement was found to be due primarily to two factors, the marginal improvement in insulation afforded by the new ceiling insulation over the existing "*insulfluf*" and the low rate of heating of the homes. The second factor introduces a major risk in terms of the upgrade contributing to increased thermal comfort; that is, if the householders do not heat the houses then adequate thermal comfort will not be obtained.
- It was clear that the simple insulation upgrade that involved only one aspect of the building fabric was not a complete solution due to the poorly built (in terms of insulation) and not well heated public HNZC housing. If improving indoor thermal comfort and at the same time improving energy efficiency at homes were the goals, then more intensive housing insulation measures or better home energy efficiency technologies would need to be applied.

Other investigations, however, have indicated that there would be some health benefits from such types of upgrades, especially for the health impaired in the North Island. Findings are summarized below.

1.4.5 Health and housing

A study by Howden-Chapman et al., 2007 [22] investigated whether insulating existing houses in NZ had an impact on improving occupants' wellbeing. Insulation levels were similar to the ones provided by the HNZC programme. Their findings suggested that "insulating existing houses led to a significantly warmer, drier indoor environment and resulted in improved self rated health, self reported wheezing, days off school and work, and visits to general practitioners as well as a trend for fewer hospital admissions for respiratory conditions."

Their study recognised that badly constructed and older houses were difficult and expensive to heat and that inadequate warmth in the home can have health consequences for the occupants, particularly during winter. The study suggested that: "The efficiency of domestic energy is linked with health because money spent on energy cannot be spent on other necessities such as food," and that "houses that are cold are also likely to be damp, and this can lead to the growth of moulds, which can cause respiratory symptoms".

The Howden-Chapman et al. results with regards to improvements in indoor temperatures after a retrofit agreed with our study, as they found that "insulation was associated with a small increase in bedroom temperatures during the winter (0.5°C) and decreased relative humidity (-2.3%), despite energy consumption in insulated houses being 81% of that in uninsulated houses" (i.e. a 19% reduction). They concluded that "fitting insulation is a cost effective intervention for improving health and wellbeing and has a high degree of acceptance by the community, policy makers, and politicians."

1.4.6 International studies

There have been a large number international studies which have attempted to provide a cost-benefit analysis for potential upgrades in the existing residential stock. A full review of such studies has been documented by Lloyd et al., "Monitoring of Energy Efficiency Upgrades in State Houses in Southern NZ" [23].

There is some evidence, particularly for smaller upgrade projects, that residential housing energy retrofit programmes are successful in reducing energy consumption. One study in the UK (York) monitored 4 houses that had been retrofitted and found a 50% reduction in energy consumption after the upgrade. They also suggested that further significant reductions are technically and economically feasible[24].

The efficacy of upgrade programmes has been found to be somewhat controversial as they can be expensive and can often produce ambiguous outcomes. This has been particularly true in terms of levels of energy reduction, where for instance, Milne and Boardman found in the UK that "in most cases of domestic energy efficiency retrofits, there are varying degrees of differences between the predicted energy savings, based on the calculated heat loss reduction, and the actual energy savings achieved in practice" [25].

"The percentage of potential energy savings that are taken as improved comfort is known as the 'comfort factor'. This has to be taken into account when estimating the effect of improvements to the housing stock" [26].

In general the findings of several studies have suggested that lower levels of energy reduction than expected occur due to a trade-off between taking the savings as thermal comfort rather than decreasing their energy consumption [27], especially in houses that are not fully heated. In a cost-benefit study, Clinch and Healy suggested that improving energy efficiency in housing will not necessarily result in reduction in energy use, with much of the potential energy reduction cost savings instead taken as increased comfort in underheated houses [19]. A study by Skumatz evaluating a USA utility energy–conservation programme found that 75% of the benefits of the programme were given by reduction in energy consumption while the remaining 25% were given to improvement of thermal comfort [28]. These results agreed with a study by The Energy Saving Trust in the UK, which found similar percentages [29]. The results were also consistent with a UK study by Milne and Boardman which monitored retrofitted low income households. The study by Milne and Boardman found that "at a temperature of 16.5°C, 30% of the potential energy savings were taken as an increase in comfort temperature" [25].

In a study involving different economic sectors in the UK suggested that the amount of energy reduction and temperature increase depended upon the level of income of the householders. In this study the authors concluded that in low income homes the benefits would be divided into 40% of energy savings and 60% improvement in thermal comfort, while over all economic sectors the division would be 70% energy savings and 30% improvement in thermal comfort [30]. Two Irish studies by Conniffe and Scott [31] and Sheldrick similarly concluded that low income households realise almost all of the benefits of improving energy efficiency as improved comfort. These researchers found that after a retrofit programme was implemented "fuel bills fell by only 2.7% which suggested that the comfort benefits of the programme were substantial" [32].

A Swedish study by Gustafsson concluded that the optimal level of extra insulation on existing buildings depends on the optimal heating systems with a high degree of interdependence. Significantly they suggested that it is essential that the two variables, insulation and degree of space heating, should be optimized simultaneously [33].

On the other hand, some studies have suggested that retrofit programmes may not be attractive in terms of simple payback times. A study undertaken by Guler et al. exploring options for the Canadian residential sector concluded that the energy cost savings potential of retrofit upgrades in Canada was small (0 to 8% of the total energy consumption for the Canada residential sector). Their findings suggested that upgrading the heating system alone would provide the largest energy cost savings potential, followed by basement insulation upgrades, ceiling insulation upgrades, and thermostat upgrades. Long simple payback times were calculated leading to the conclusion that "it can not be realistically expected that any household could consider energy efficiency upgrades with payback periods 20 years or longer to be feasible" [34].

Many people recognise that retrofit programmes might provide benefits other than reducing energy consumption, especially if designed for low-income householders [35].

The largest residential upgrade project undertaken in the UK has been the Warm Front (WF) project which encourages retrofitting of existing dwellings to reduce negative effects of people living in cold homes. After monitoring houses over two winters, several papers have been published analysing the impact of the programme. One study resulting from this work, Hong et al., concluded that "…the potential improvement in energy efficiency from the installation of draught stripping, insulation, and gas central heating system was not observed," and that "there appears to have been no reduction in fuel consumption as a result of the WF measures, even after taking into account the increased temperature in the post intervention properties" [36].

The WF programme is part of 'The UK Fuel Poverty Strategy' [37] which aims to reduce fuel poverty by providing grants for insulation and space heating systems to low income householders. Results by Oreszczyn et al. for the same WF project suggested that there had been an increase of 1.6ºC in temperatures for living rooms and 2.8ºC for bedrooms after houses were fully upgraded and central heating was installed, although only a 0.7ºC temperature increase was recorded for the living area in houses which had only the insulation installed [38]. In terms of energy reduction, the Hong study found that the projected potential energy reduction savings of 61% predicted by their model was not found even after normalising by area and heating degree days. The decrease in energy consumption found by Hong et al. was found to be between only 10% – 17% due to insulation and 0% due installation of an efficient central space heating system. They suggested that the difference between the modelling and the monitoring could be due to the rebound effect, errors in calculation, or due to the simplicity of the model (assumption on air tightness, % of area insulated, efficiency of the heating system) [36].

Conclusions regarding the efficacy of retrofitting programmes throughout the world depend on current heating and insulation practices. Where houses are fully heated, insulation upgrades and heating system efficiency improvements have led to a reduction in heating energy requirements. The benefit is increasingly less where insulation levels are already decent. Where houses are not normally fully heated, retrofits are more likely to increase comfort than reduce energy use. This is more likely when the retrofit had been accompanied by a heating system upgrade that allows a significant increase in energy use for the same cost.

Findings of the Warm Front monitoring study are in good agreement with findings of our previous report. These lead to the conclusion that further work was needed. Thus this second report explores other options and aims to provide recommendation on different upgrades stressing the urgency to improve the efficiency of existing houses in NZ.

CHAPTER 2 : METHODOLOGY

2.1 Background: From heat losses and solar gains to energy requirements

In cold climates unless the passive solar design is good, buildings usually require extra energy to achieve an adequate indoor thermal comfort. Buildings with high heat losses will provide little resistance to heat flows requiring more energy to maintain comfort levels. A description of heat losses and the ways to reduce such losses is detailed below.

2.1.1 Heat losses through elements of the building fabric

Heat will always travel from warm to cold. If comfortable indoor levels are to be achieved in a house during winter months, a difference between indoor and out door temperature will exist. This temperature difference is defined as the *net temperature difference* (NTD). In order to maintain a temperature differential, energy will need to be applied to the interior. One source of this energy is the sun. However since many houses are not sufficiently well designed to capture and store enough solar energy, most residential occupiers purchase space heating energy.

When there is a net temperature difference, constant heat flow from the indoor environment to the exterior through the building fabric will occur. Here is where the materials composing the building fabric play a key role, as some materials will provide little resistance to heat transfer requiring more energy to maintain the NTD. The amount of heat transfer (heat losses from *inside* to *outside*) will thus depend on the materials composing the building fabric. Each element (ceiling, walls, windows, and floor) is made out of different materials. Each material has its own thermal properties (e.g. thermal conductivity) and dimensions (e.g. thickness). The addition of various materials will provide a total resistance to heat losses through each element.

Heat losses can be reduced by adding insulation. There are different types of insulation which work in different ways towards reducing heat transfer:

- Bulk insulation works by resisting heat flow by conduction and convection. Bulk materials like fibreglass, wool, expanded polystyrene, etc. are made of low thermal conductive materials with small enclosed air pockets. Still air is a very poor conductor of heat, so these materials rely on this trapped still air to perform well. Thus, the way that these materials are installed is very important as their performance will be reduced if they are squashed, which reduces the thickness, or if they are installed with gaps, which allows for air convection around the material. Also bulk insulation needs to be kept dry, as moisture content will also reduce thermal performance.
- Reflective insulation works by reducing radiant heat transfer. These materials have highly reflective surfaces with low emissivity (e.g. aluminium foil). As with all insulation, careful attention is required during installation. Performance is compromised if the face of the material is touching the opposite wall (as conduction of heat is then allowed) or when dust settles on the surface (reducing the reflective property).

Heat losses (measured in watts/kelvin) can be then defined as the heating power that must be added continuously to the house to maintain each degree of temperature above ambient. Lowering heat losses by conduction installing insulation will result in increasing the thermal resistance of the material, the reciprocal of heat loss, normalised to a unit area. This is known as the R value, and is measured in m^2K/W.

2.1.2 Heat losses by infiltration

Heat losses by air infiltration refers to warm air that escapes the building through cracks, windows, etc., and is replaced by cold air.

It is difficult to estimate the air tightness of a house without conducting physical tests. Sealing and re-seating windows will lead to a reduction in heat losses by infiltration and thus will further reduce the heat loss of a house. A study of New Zealand house retrofits has shown that a reduction in air infiltration of 50% can be expected by re-setting windows and doors, and caulking leakage, openings in the interior lining with a sealant. A 25% reduction can be obtained by using mostly foam strip materials on doors and opening windows [39].

Once heat losses and gains are estimated for a house and location, estimates can be made of the annual additional purchased *space heating energy* needed to maintain the house at comfortable conditions.

2.2 Overview of testing methodologies

2.2.1 Existing methods to determine thermal performance of building materials and structures

A Heat losses of building components and structures

A.1 Components

Guarded hot box (ASTM C 1046 In-Situ Measurement of Heat Flux and Temperature on Building Environment Components): The laboratory device of choice to measure the thermal conductivity of building components is a guarded hot box. This well insulated box surrounds a one square metre section of the material in question, and holds one side of the material at a high temperature, and the other side at a low temperature. The heating power needed to maintain the temperature difference is measured. The specific heat of a sample can be measured by simple calorimetery, that is, by immersing the material of known temperature and mass in a water bath of a different known temperature. The final temperature achieved by allowing the two materials to reach thermal equilibrium allows a calculation of the unknown specific heat of the sample.

Dynamic techniques - Gustaffson probe: The thermal resistance of some homogeneous building materials can also be measured using dynamic techniques, that is by solving dynamic heat flow equations to give thermal conductivity and thermal emissivity. An example is a Gustaffson probe. This probe applies a small pulse of heat to a surface and measures the time and changing temperature of that surface. The temperature changes observed allow the calculation of several thermal material properties, namely the thermal diffusivity, conductivity, and volumetric specific heat capacity. Thermal conductivity is the reciprocal of thermal resistance, and the volumetric heat capacity can quickly be used to determine the total building thermal mass. This technique was first reported in Gustafsson 1990 "Transient plane source techniques for thermal conductivity and thermal diffusivity measurements of solid materials".

A.2 Parts of buildings

Heat flux sensors: The thermal properties of large sections of walls, floors, and ceilings are more difficult to obtain but can be measured *in situ* with the use of appropriate thermal flux sensors. Such sensors can consist of parallel metallic sheets with embedded temperature sensors. The sheets are placed on surfaces, and by measuring the (small) temperature drop across the sheets, the heat flow through that wall section can be calculated. The section of the wall can be chosen to include some thermal bridging from joists, etc.

Studies using this technique include one by BRANZ documenting a survey of house insulation [40]. Others studies suggest that component level determination of R-values is possible *in situ* [41],[42],[43]. A standardised test method is available (C1155 Thermal Resistance of Building Components from *In Situ* Measurements with C1046).

A study by BRANZ looking the importance of the way insulation is installed found that "in practical building terms … for ceiling insulant, having cavities both above and below the insulant, it is possible to realise the full value with achievable standards of good workmanship of a few mm. But in the case of walls this is not so. Even 'good' workmanship is not enough, in that case, gaps of less than visible width (1mm) are likely to drastically undermine the insulation value." [44]

A.3 Complete buildings

A complete building has several additional characteristics which further complicate experimental heat transfer measurements. Some of these complicating factors include:

- Internal thermal stratification means slightly more heat is lost high up on the walls and ceiling.
- Air ingress (draughts) carry heat out of the building depending on the internal temperature and external wind speed and direction, and is thus not constant.
- The effectiveness of insulation is very dependent on details of installation, which vary.
- The complexities of three dimensional thermal bridging in corners and complicated geometrical structures are not easily accounted for.

There are several variations of whole house testing procedures which attempt to measure the thermal performance of compete buildings. These include the co-heating method originally developed by Palmiter et al. during the 1970s, which has been revived by Judkoff et al. during the 1990s and the STEM procedure used by Sondereger during the 1980s [45] and Stoekline during 2001.

The co-heating (whole house calorimeter) test is a method of determining the actual heat loss due to combined fabric and infiltration losses of unoccupied dwellings. It does so by measuring the heating power required to maintain a constant temperature difference between the interior and exterior of the building under steady-state and repeatable conditions. Tests are done in unoccupied buildings with all electrical and heating systems inside the dwelling turned off and all ventilation system vents and other openings kept closed. In order to maintain an even temperature profile throughout the dwelling, circulation fans are used to mix the internal air. In order to maximise the net temperature difference, the co-heating tests should be carried out in winter when the external temperatures are lower [46][47][48]. The procedure was originally described by Palmiter et al. in "Low cost performance evaluation of passive solar buildings" (1979) [49]. Variants of this test can be performed in combination to determine in-situ delivered heating and cooling efficiencies and reductions to the building loss calculation due to various retrofit measures [50].

Advantages of this method are that results are for real configurations, a situation which is usually hard to model as many assumptions need to be made. Results of these tests can help to correct modelling and to have a better understanding of thermal performance in order to predict energy consumption. Disadvantages include that the houses need to be unoccupied for long periods of time. Also, it has been suggested that infiltration rates could increase due to the test itself [51].

The Short Term Energy Monitoring (STEM) test is a test usually consisting of a 3-day protocol in which the key thermal performance parameters of a building are determined by measuring the buildings response to certain external and internal excitations [52][53]. These include a co-heating test to determine the buildings' overall heat loss coefficient; a cool-down test to determine the buildings' heat capacitance properties; a floating temperature test to determine the buildings' response to solar energy absorbed through transparent and opaque surfaces; a blower-door test or tracer-gas test, or both, to determine the infiltration rate; measurement of solar energy and other meteorological variables. The method includes mathematical correction and parameter estimation techniques to account for the effects of solar energy and varying weather conditions on the building.

Co-heating tests were carried out recently (2006) by the Centre for the Built Environment at the Metropolitan University [54] in the UK. Findings of their study have shown that the postulated results from insulating the building fabric were usually higher that those obtained from co-heating tests. In some cases the discrepancy was as large as 100%. Reasons for this discrepancy were suggested to be that insulating elements had lower thermal resistances in practice than given by the manufacturers, the effects of thermal bridging, and that air infiltration might increase slightly during the test due to high thermal stresses imposed on the building fabric and joints. In this study, all the tests were done over a period of a few days and therefore results needed to be corrected for solar gains.

STEM tests were also carried out by the National Renewable Energy Laboratory in the US (NREL) and reported by Judkoff et al. 2000 on "Side-by-Side Thermal Tests of Modular Offices: A Validation Study of the STEM Method" [55] . Another study monitoring the performance of 70 houses across the US found that on the average measured energy performance using STEM tests agreed with predictions using computer modelling, although for individual buildings the results differed considerably [56].

Air ingress

In addition, air heat losses by infiltration need to be determined. Methods of determining air infiltration rates include:

Tracer-gas tests which measure air infiltration directly (at naturally driven pressure differences) by measuring the decrease in concentration over time of a gas (usually sulphur hexafluoride) injected into the building [57][55]. Other tracer-gas techniques include the constant concentration and constant injection methods [58] (ASTM E741 Determining Air Change in a Single Zone by Means of Tracer Gas Dilution). This test requires several days of testing.

Blower door tests determine the size of construction cracks and holes in the buildings envelope by depressurizing and/or pressurizing the building with a large fan [42]. This test can be conducted in about an hour per house. Blower door tests typically measure the air change rate developed by a 50 Pascal pressure across the building envelope. This is substantially higher than natural pressures that force infiltration during the normal operation of the building. Natural pressures are on the order of 1 to 10 Pascals. BRANZ has developed some approximate methods for estimating average annual infiltration from air leakage tests made at 50 Pascals [59] (ASTM E1827 Air tightness of Buildings using an Orifice Blower Door (specific adaptation of E779)). Estimating infiltration from a blower door test is difficult. However depressurising a house with a blower door can help architects and builders get a good sense of the location of air leakages sites. During the test it is easy to feel the source of draughts throughout the house.

In situ tests: The importance of having in-situ thermal tests on buildings have been highlighted by a Russian study: "The performance of an existing energy using subsystem,.. is often not well known and can vary considerably by region and even among normally identical buildings" [60].

B Existing methods to predict the thermal performance of buildings:

Steady state methods consider the thermal resistance of components but do not usually take into account the thermal mass of building elements. Such methods analyse the building using steady state conditions inside and outside. Heating Degree Days for particular locations can then be used to calculate annual heating requirements.

Dynamic methods solve the dynamic heat flow equations to give transfer functions and hence determine the dynamic heat flows and indoor temperature data for each calculation period (often a few minutes) of a simulated year (e.g. dynamic computer models VE, Suncode, Trnsys, etc).

C Ways to interpret outcomes: LCA/CBA

Cost-Benefit Analysis (CBA) is a procedure used to evaluate the economic viability of a project being considered [61][62]. Typically this type of analysis considers only direct costs and benefits. However, a more thorough form of this analysis would take into account all externalities. "An external cost (or benefit) is a cost (or benefit) resulting from an activity which is not borne (captured) by the person engaging in that activity, e.g. the carbon dioxide produced from energy generation that will impose environmental costs (global warming) which will be borne by other sections of society. The consideration of such costs and benefits is extremely important in CBA, as we are considering all of the costs and all of the benefits to the whole of society. The difficulty is that these external costs and benefits are usually not exchanged within markets, so there is no price to reflect their value. A number of non-market valuation techniques are used to place monetary values on these externalities" [19].

A Life Cycle Analysis avoids the difficulty in pricing every cost and benefit. Instead an inventory of different types of effects is created, for example, energy use, financial cost, and CO_2 emissions. The method has been described in many studies and standards [12]. It included the following steps:

1) Goal and Scope Definition – the boundaries of the system under consideration
2) Inventory of Inputs and Outputs of System – establish what do we want to assess
3) Assessment of Impact of each Input, Output
4) Evaluation and Interpretation of Impacts

Over the past years, several international programmes have been designed to estimate the impact of buildings. They all define their own boundaries and take into account their own local situation. They include BREEM, BRE, ENVEST LCA from the UK, CREEM from Canada, Green Guide to Specification (UK), LISA and LCA Design from Australia, Athena and BEES from the USA, Ecoquantum form Holland, and Energy Assessment Model from Ireland, UK.

For papers investigating buildings using this methodology see Clinch et al (Ireland), Mithraratne (New Zealand) and Guler (Canada).

Both Cost Benefit Analysis and Life Cycle Analysis require several assumptions that are variable, difficult to justify, and are highly influential on the outcome. A useful lifetime of the building and upgrade components must be established, which can vary from a few years to over 100 years. For Cost-Benefit Analysis, a discount rate for monetary costs must be estimated, which implies that long term benefits are worth very little. Finally, cost savings may be nil because of rebound effect.

2.3 Our methods used to determine thermal performance of residential buildings

As part of our research, two NZ state houses were upgraded and monitored to identify improvements in their thermal performance. One of the houses was used as a '***base case***' to explore other upgrade options by modelling. The following methodologies were used:

- Manual calculation
- A calorimetric experiment to measure heat losses

- Steady state computer modelling to estimate annual heating requirements and hours of thermal comfort

2.3.1 Method 1: Manual calculation (Heat Losses)

The effective thermal resistance of the house was first calculated manually by taking into account total heat losses by conduction (through the building envelope materials) and through infiltration (through air ingress).

Heat losses by conduction were calculated by taking into account the resistance to heat flow of each element and the percentage of area that that element accounts for. Construction details that include the thermal conductivity and thickness of each material were taken into account by considering the effect of thermal bridging. Wall, floor, ceiling, and window thermal resistances were calculated according to New Zealand Standards 4124-2006 [63]. NZS 4124-2006 describes methods for determining the total thermal resistance of parts of buildings in steady state environmental conditions and it is intended to be used as a means of compliance with the relevant requirements of the building code. The thermal conductivity of materials was obtained from values in the standard and ASHRAE Fundamentals [64]. U values for each element of the building envelope were then calculated as explained below.

Heat losses by air infiltration were estimated by house characteristics and exposure class [65].

Calculating the house heat loss involved several steps

a. Calculating wall and floor bulk thermal resistance from components. Ceiling thermal resistance was referenced from the BRANZ House Insulation Handbook [66].
b. Determining overall heat loss from the area of each component and the thermal resistance of each component, and summing the result to obtain the total conductive heat loss (HL_C).
c. Estimating infiltration heat loss (HL_I) as in Bassett 2001 and adding this to the conductive heat loss to obtain the total heat loss .

The total heat losses ($HL_C + HL_I$) are then divided by the total building envelope area ($Area_T$) to provide the total conductance of the building envelope known as U-value of the house. The inverse of this value is the resistance of the building fabric known as R-value.

$HL_C + HL_I = HL_T$ (W/K)
$HL_T / Area_T$ = Effective U-value (W/ m^2K)
1/U-value = Effective R-value (m^2K/W)

Uncertainty in Calculated Heat Loss according to NZS 4214

Testing laboratories can determine the thermal properties of a particular building component with a relatively high accuracy (1% or better) if it is a standard product such as glass fibre. However, the heat losses for a whole building can be more difficult to obtain to better than 10%.

Uncertainties result from variations in the materials, less than ideal workmanship, and assumptions inherent in the NZS 4214 model. Construction materials can vary in their thermal properties by up to 10%, although the variation depends on the type of material[63].

Workmanship affects the installed thermal resistance of air gaps and insulation. This dependence increases as more insulation is added. A 5-mm gap between joists and installed ceiling batts can result in a 40% reduction of thermal resistance in a ceiling cavity [67].

Some thermally complicated components are difficult to model. For example concrete block wall calculations are complicated by the thermally conductive cement mortar. In a paper examining such walls, empty core concrete block walls with known concrete thermal conductivity had measured U-values that were within 10% of calculated values. However, for masonry walls with core insulation, measured U-values differed by 0% to 40% from calculated values. [68].

When calculating heat loss for a house the many small independent uncertainties statistically tend to offset each other. Thus even with the variation in materials and construction details, it has been shown that the calculation of component thermal properties according the NZS 4214 can be accurate to 10%[69].

Estimating infiltration by visual inspection is not very accurate. Infiltration heat loss estimates are accurate to 100% or a factor of two. Given that infiltration heat loss is estimated to be about 10% to 20% of conductive heat loss, the uncertainty for the sum total heat loss is estimated to be 12% to 17%, depending on the level of insulation.

2.3.2 Method 2: Experimental thermal testing (Heat Losses)

Our method consisted in measuring the U value for the whole house at the different upgrade stages. This was done by doing a co heating test as described above.

The thermal performance of the building system can be most easily analysed assuming steady-state conditions via a lumped resistance model (both indoor and outdoor conditions are taken as steady, non-changing) or the analysis can consider the building's dynamic behaviour using a thermal modelling package [70]. See Appendix A for more details.

A Whole house calorimetery (Co-heating)

A simple way of including most of the complicating effects into the measurements of thermal properties of a house is to directly measure the rate of heat loss from the entire house. This can be done by heating the house with a known quantity of energy per time and observing the final temperature difference achieved. Additionally the speed in which the house heats and cools down can be used to calculate thermal mass.

Ideally this measurement should be carried out in a situation where the ambient conditions are stable and controllable. Obviously this would be difficult for an entire house and so in a real experimental situation the analysis has to cope with some changes in ambient conditions (including changes in air ingress).

This type of test could be done either by measuring solar gains and adding these to the heat input or by measuring during night time when heat gains from solar energy are zero.

Limitations of whole house calorimetery

The whole house calorimeter type of measurement can of course only be done during a single night if the thermal mass of the house is sufficiently low such that temperature variations caused by solar inputs from the preceding day can be ignored. This situation was the case for both houses investigated. Error analysis was performed on all results to assess the possible variance of the lumped R values obtained.

The simple model used to calculate effective heat loss assumed a constant internal temperature. In an empty house, with no movement, the near still air will stratify as the warm air slowly rises to the ceiling. Fans installed to maintain air flow in the house will reduce stratification. Tests in an experimental chamber suggest that a temperature difference of 3 degrees floor to ceiling can be reduced to less than 1 degree with the use of a fan capable of cycling room air 20 times an hour.

Whole house co-heating is an observational method. Controlling every part of the environment as with a controlled experiment is not possible. Methods must be developed to deal with a variable site environment. Our method looks at the rate of change of internal temperature. When the internal temperature has not changed more than 1/3 of a degree per hour for 4 hours, the house was considered to be in a steady state condition.

B Measurement Equipment

Equipment used for taking the relevant measurements included household equipment (indoor measurements and heating equipments) and ambient equipment (weather station). A description of the equipment is detailed below.

B.1 Household measurement equipment

House Heating Energy input

Electric resistance heaters were installed at a heating level of close to 2 kW per 20m² of floor space. A Metec ES8 power meter was installed for each heater and fan to measure variations in output energy during the time of the test (see fig. 5). The meter produced 800 impulses per kilowatt-hour. These pulses where counted and stored at 5 minute intervals by a Gemini Data Logger TGPR-1200. The pulse counts where downloaded weekly and stored in a database for extraction into Excel.

The heaters produced an indoor room temperature of about 32ºC for the ambient temperatures presented during the monitoring period. In order to prevent thermal stratification in the rooms, several circulating fans were installed to generate vertical internal air movement. The total electrical power used by the fans was added to the space heating value.

House Temperature and Relative Humidity: Temperatures within the houses where measured using HOBO Data Loggers. The logger is the size of matchbox, and can record 7,944 data points. When recording both temperature and humidity at 5 minute intervals, the device can record for just over 13 days. Temperatures were measured using an IC temperature sensor accurate to +- 0.42ºC when 0<T<40. RH is accurate to within +- 5% when 5<T<50 ºC and 5%<RH<95%. The temperature time constant was 15 minutes when the sensor was enclosed in the box as shown. See Figure. 2.

Figure. 2. HOBO

A HOBO Shuttle 'data transporter' was used to download data and 'relaunch' each HOBO in the field, without needing to use a PC (typically 10-12 loggers per house).

Temperature and humidity data was downloaded onto a PC using the HOBO Boxcar v3.7.3 software. The software saved each download session into a '.dtf' file. Temperature and humidity data was then exported into a comma separated variable file (.csv) for further processing.

House Air infiltration: While the fabric of a house keeps the elements largely at bay, the air within the house is not so easily contained. The inside air is gradually exchanged with outside air as it filters through cracks and porous surface. The air change rate is typically expressed volumetrically, in air changes per hour (ACH).

When a building has no forced convection system, the pressure difference between the inside and the outside is low and variable. The natural pressure difference depends significantly on the inside/outside temperature difference, as well as the pressure of wind and distribution of leakage sites around the house.


Figure 3. Blower Door

An Infiltec E3 blower door shown in fig. 3 and a micromanometer was used to measure air changes near 12.5 and 50 Pascals. The data was analysed in accordance to ASTM E 1827 – 96, Standard Test Methods for determining air tightness of Buildings Using and Orifice Blower Door. This was used to quantify the amount of air leakage in both houses after each upgrade, to estimate how much heat loss occurs through air infiltration.

External doors and windows were all checked to be closed during the monitoring period. Annual average infiltration was estimated from air changes per hour at 50 pascals pressure difference (ACH50) by correcting using a correlation developed for exposed New Zealand houses [71].

Calibration of Temperature Sensors: Twenty HOBO temperature sensors were calibrated against a RT200 platinum resistance thermometer. The temperature sensor probe was uncoiled from inside the HOBO box and immersed in ice water. The data loggers were set to record every 10 seconds. Every minute the platinum resistance thermometer temperature was recorded. Temperatures were recorded over an hour, as the temperature rose from zero degrees centigrade slowly towards ambient, and warmer, after hot water was added. At no time was the temperature in the water observed to change more quickly than 0.1 deg C per TK. This was much slower than the temperature probe time constant of 2s, so the water temperature at each sample was considered to be constant.

Each platinum resistance measurement was paired with the logger measurement taken at the same time (within 5 seconds). The slow change in water temperature compared to sensor time constant allowed the assumption of constant water temperature to be made. An XY plot of each sensor measurement against the platinum resistance thermometer was produced, and a linear regression calculated. The slope and offset of each regression was used to scale the measurements from each sensor. Calculations where performed using Excel's SLOPE, INTERCEPT, and PEARSON functions.

After the data collection, a check of the calibration was performed. The probes were immersed in a slowly warming stirred water bath, and the corrected (scaled) measurements again compared to the calibration thermometer (the RT200).


Figure 4. Weather Station

B.2 Ambient measurement equipment

A local weather station was installed on the roof of one of the houses, as can be seen in fig. 4, to collect data for ambient temperature, humidity, wind speed and direction and insolation. The equipment included:

Site Temperature and Humidity: Site temperature and humidity was measured using a Vaisala HMP45a probe in a radiation shield.

Site Solar Insolation: Direct and diffuse solar radiation was measured using a Kipp and Zonen CMP11 pyranometer. See Fig 5. This instrument measured global irradiance at the site from 310 to 2800 nm.

The logger was programmed to apply a scaling polynomial, based on the factory calibration: I (W/m^2)= 196.5 x (mV).

Site Wind Speed: Site wind speed was measured by a Vector Instruments A101M pulse output anemometer. A 20 metre shielded cable connected the anemometer to the data logger. The logger was programmed to count pulses and record the average wind speed every five minutes. The logger was programmed to apply a wind speed scaling polynomial to convert the output to the proper units v (m/s) = 0.1 x (Hz).

Site Wind Direction: Site Wind Direction was measured using a Vector Instruments W200P/L wind vane. The logger was programmed to apply a scaling polynomial: θ (degrees) = 0.072 (mV * 10^3).

Downloading Data: Data was downloaded into a computer every few days for further analysis.

Figure 5. Site Solar Insolation Measurement Device

Figure *6. Site Wind Speed Measurement Device*

Figure 7. Site Wind Direction Measurement Device

2.3.3 Method 3: Static simulations (Annual Heating Requirements)

A steady state computer model was used to estimate annual energy requirements for space heating for each configuration. The model used was the Annual Loss Factor (ALF3) model developed by BRANZ to model NZ houses [72]. This model is a steady state model calculating heat gains and losses and using historical local climate data. The model has the option of 4 different heating schedules at 3 different temperature set points. It uses data from the following sources to estimate annual heating energy required:

a. House heat loss estimated from construction details.
b. Annual useable solar gains, calculated from window details, shading, and heating schedule.
c. Heating Schedule
   EVE: Evening 5pm-11pm.,
   ME: Morning and Evening, 7am-9am and 5pm to 11pm.,
   ALL: All day heating, 7am-11pm (ALL), and
   24H: Continuous heating (24H)
d. Temperature set point 16, 18, or 20ºC

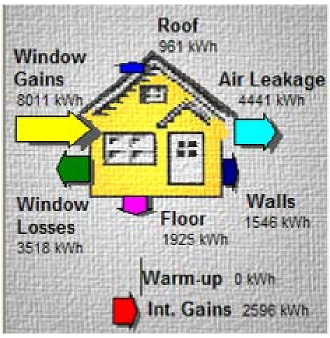


Figure 8. ALF

In addition, internal gains from the occupants and warm up loads from the effective thermal mass are also taken into account. The program estimates the energy required for space heating for the specified configuration. Physical information about our houses (dimensions, location, etc.) together with results of our testing (i.e. the real R values) were input to the program to estimate the energy requirements for space heating.

ALF was limited in that the simulation assumes that the entire house was being heated to the set schedule. Heating schedules and set points temperatures are fixed (no options is given to differences in heating schedules for week and weekends days). Heating one area or room of a house can be approximated by modelling the single room as a small house with some window-less walls.

Also in ALF, thermal mass is simply modelled. Finally there is no way of quantifying hours of thermal comfort, say, from afternoon sun, which is beyond those hours set by the heating schedules.

2.4 Method used for our Cost-benefit Analysis

A life cycle analysis takes an inventory of all possible effects to aid in decision making. A cost benefit analysis uses this inventory to suggest that improvements should be made only when the overall benefit is positive, when all possible effects have been priced, discounted, and added together. In an ideal world optimal decisions could be made by including all of these components. Quantifying the many benefits of an improved house, including comfort, heating flexibility, satisfaction, social connectedness and inclusion, and many others, is very difficult. Even if they can be quantified, the next step of pricing the effects for a cost benefit analysis is also difficult.

However, the decision making process can be improved even with partial information. We have enough information to predict upgrades costs, and their effects towards reducing recurrent heating energy, fuel cost, and CO_2 emissions. We can thus show how to reduce them in the most effective way, that is, with the least incremental cost per incremental improvement.

Keeping *initial* and *recurrent* costs separate in our analysis has another practical benefit for rental properties, since these costs are borne by separate parties. Tenants want to minimise annual energy costs while remaining comfortable. The country has a goal to minimise annual CO_2 emissions. The owner wants to achieve these results in an efficient manner, starting on the projects that achieve the most effect for the least capital cost.

It is thought that basing project decisions on the quantitative improvements in internal temperatures, financial costs, energy use, and CO_2 production will help to produce sound retrofit decisions for New Zealand.

2.4.1 Inventory: What have we quantified?

We have quantified CO_2 emissions associated with space heating, thermal comfort levels achieved and costs savings for different upgrade options.

An inventory approach has allowed us to choose retrofits based on minimising recurrent CO_2 emissions for indoor situations that meet minimum temperature levels and specified heating cost levels. With this inventory approach, however, it has not been possible to rank all of the retrofit options for a house as a procedure has not been identified for unambiguously ranking CO_2 emissions against cost [73].

2.4.2 Impact: Assessment and evaluation of outcomes

The effect of each upgrade option on the environment (recurrent CO_2 emissions), indoor comfort (temperatures) and energy consumption (and hence cost) has been evaluated.

In order to quantify the benefit of different upgrade options and provide advise on an optimal retrofit path for existing houses, we have ranked the different upgrade options in a savings to investment ratio as per Gorgolewskis' method [74]. This method provides a ranking of the economic performance of an investment. It does so by dividing the present value of the total lifetime energy saving by the investment cost. The higher the ranking, the larger the return on an investment. In addition, recurrent CO_2 emissions reductions due to the upgrades are also presented and only upgrades that reduce recurrent CO_2 emissions are considered as possible upgrade options. Upgrades that increase recurrent CO_2 emissions are rejected.

2.4.3 Data used for our Analysis

Recurrent energy, cost and CO_2 calculation (from space heating) were calculated from different sources. Annual energy requirements were estimated using BRANZ ALF3 model. Costs of heating energy were taken from the Ministry of Economic Development [75].

Heating system efficiency and costs, and fuel costs and CO_2 emissions are used as reported by Westergard [76], Ministry for the Environment [77][78], Ministry for Economic Development [79], Energy Studies, University of Otago, [80].

Different sources were used with the purpose of evaluating costs associated with purchase and installation of materials. These included data obtained from Rawlinsons [81], The Building Economist [82] and from the present project upgrade experience.

2.4.4 Limitations from our Analysis

The analysis examined changes brought about by retrofits to the dwellings and the use of the dwellings. Additional costs or benefits beyond the dwelling, for example, changing transport patterns brought about by more comfortable homes, were excluded. Increased temperature has been shown to have positive health outcomes. While noted, these benefits have not been quantified in our analysis. Furthermore it has been assumed that air quality regulations in NZ are sufficient to control particulate emissions from wood fires. Therefore these impacts have not been included or quantified.

Financial cost: energy and CO_2 for construction and operation are tallied. Costs, energy and CO_2 attributable to demolition are ignored as it is a small part of the total as recognized by Mithraratne. Also excluded from this analysis is any consideration of the other known effects noted above, namely particulate emissions, health improvements linked with temperature rises, construction waste products and other pollution.

Cost and emissions from maintenance and replacement of heating systems or building materials are not taken into consideration. Construction embodied energy and carbon data do not include transportation to the building site, at a significant energy and carbon cost. CO_2 form embodied energy of building material are only presented as reference only.

BRANZ ALF3 allows for only a limited selection of heating schedules, and provides only a rough estimate of partial house heating.

Also the effect on choosing an optimum heating system does not take into account the impact that this choice will have in the national grid (e.g. findings of a BRANZ study [83] suggests that electricity grid will not cope with 100% of houses heated with heat pump). Our analysis only takes into consideration operational CO_2 emissions, cost and comfort levels delivered by the heating system.

Construction costs are estimates, including labour that is used for low volume construction projects. Costs will likely decrease in larger projects.

CHAPTER 4 : HOUSES DESCRIPTION

This chapter describes the upgrades done in two houses that were retrofitted and monitored over 4 months during May-September 2006.

4.1 Existing Conditions

Both houses were located in an outer Dunedin suburb known as Brockville. This suburb at around 240 m above sea level has good sun access but with considerable exposure to the wind. Houses in the suburb were mostly built by HNZC during the 1960s. A description of each house is detailed below:

House 1 (shown in fig. 10) was located at 118 Cockerell St. It was a 3 bedroom, 89.50 m² house with masonry veneer construction, a suspended floor and relatively good solar access. Walls were built with concrete block with an air gap and timber frame construction faced with GIB board but with no wall insulation. Windows were single glazed with wooden frames. The roof was a tiled hip roof with a timber framed attic. The ceiling had polyester blankets installed across the rafters on top of macerated paper, the latter being installed in between the rafters. Looped aluminium foil had been installed under the wooden floor. Both the underfloor insulation and the ceiling polyester had been installed as part of the energy efficiency upgrade package completed by HNZC some years earlier. The house had a small multi-fuel burner installed in the living area. There was carpet over the floor boards but with no underlay. A ground vapour barrier was found in the basement to prevent moisture penetration.

Figure 9. House 1: 118 Cockerell St. Brockville, Dunedin

House 2 (located at 83 Cockerell St) also had 3 bedrooms with a floor area of 84.30 m². It was built using a combination of weatherboard and brick veneer construction as can be seen in fig. 11. It was also built with a suspended floor but did not have good sun access. Windows were single glazed, wooden framed and with some of them very draughty. The roof was corrugated metal with a timber framed ceiling space. As this house had not yet made it to the HNZC upgrade programme, no insulation was found in the house except for the ceiling that had macerated paper installed between the rafters from a previous 1970s retrofit. The carpet and paint was not in good condition. The house also had a multi-fuel burner installed in the living area but against a north facing wall which blocked most of the midday sun. Mould was found in the bathroom and bedrooms walls, especially in the corners. A ground vapour barrier was not found in the basement to prevent moisture penetration.

Figure 10. House 2: 83 Cockerell St. Brockville, Dunedin

See appendix B for layouts of each house.

4.2 The Upgrades

The aim was to investigate the thermal improvement provided and economic cost of materials and installation for a selection of different glazing, insulation products, and window dressings. In addition it was hoped to ascertain the skilled labour difficulties of putting the products in place. Some components that we would have liked to have used were not found in the NZ market at a reasonable cost (e.g. thermally broken aluminium window frames). It was realised throughout the component selection process that retrofits that were too expensive would not easily be implemented on a large scale by HNZC even if they showed good performance.

4.2.1 Upgrades in House 1

In the case of House 1, the full exterior fabric was insulated at two levels depending on the location of the fabric in the house. The total external envelope area was 291.70 m² with a wall to window ratio of 2.3:1 Insulation was installed on top of the front face of the existing GIB board walls (from the inside of each room) for most of the external building envelope. It was initially thought that this would be more cost effective than completely replacing the GIB boards with insulation within the frames. Adding insulation on top of the GIB (gypsum plasterboard) was made easier with a product called 'Formaliner' which came in sheets, as a combination of GIB bonded with expanded polystyrene [84]. The polystyrene had a thickness of 50 mm and a product R value of 1.3 m^2K/W. Installing this product on top of all exterior walls meant that the room size was slightly reduced. The product, however, was difficult to install in areas that had internal services and obstructions present, such as the wet areas (including the kitchen, toilets and laundry (see fig.13). In these areas bulk insulation (fibreglass batts) was installed inside the wall framing cavity. The fibreglass batts were manufactured by 'Pink Batts' and were 90 mm and had a rated R value of 2.2 m^2K/W [85].

Figure 11. Wall insulation system: Expanded Polystyrene with Gib.

Figure 12. Wall insulation system: Pink batts on wet areas.

The existing single glazed wooden frame windows were replaced with double glazed new aluminium frame windows with argon between the panes and manufactured by a local company (see figures 13 and 14). However, the frames of the windows installed were not thermally broken. Because of the extra thickness of the 'Formaliner' the window sills needed to be wider than the original ones, and new wooden lintels were installed in addition to the new windows. The lintels were fixed to the existing wall structure to allow later fixing of curtain pelmets. The windows were also upgraded with thermal curtains including pelmets. The additional window treatment was undertaken before and after upgrading with double glazing so that two sets of measurements could be made (see results section).

Figure 13. Existing single glazed wooden frame windows

Figure 14. New double glazed aluminium framed windows.

Bulk underfloor insulation was installed by removing the existing aluminium foil and installing expanded polystyrene sheets between the joists (see figures 15 and 16). The polystyrene was 55 mm in thickness with a rated R value of 1.4 m^2K/W [86]. Existing carpet flooring was removed to provide a healthier new surface. The original wooden floor was of a very good quality hardwood (Rimu) but with often large gaps between the boards. The surface was treated by filling the gaps and polishing the floors. This process proved to be more difficult than orignally anticipated.

As the ceiling space had already been insulated with polyester blankets, which were installed as part of the energy efficient upgrade programme by HNZC, on top of macerated paper [87]; no further work was done in this area. These blankets with the macerated paper were estimated to have a total R value of 4.67 m^2K/W [1].

Figure 15. Existing underfloor insulation: Aluminium foil.

Figure 16. New underfloor insulation: Expanded polystyrene sheets.

4.2.2 Upgrades in House 2

House 2 had not been previously upgraded as part of the HNZC upgrade programme so insulation was provided to the entire ceiling space and underfloor (except underfloor to the kitchen, as the laundry was located underneath this area). Wall insulation and window treatments were only undertaken for the living area. The total envelope area for the livingroom was 76.21 m^2 and total wall to window area was 6.5:1. This reduced level of upgrade was done to assess the benefits of a lower cost option. A description of each upgrade stage for this house is detailed below.

Bulk insulation was installed inside the existing wall cavity (including internal walls) surrounding the living room only by removing the existing 'GIB' and installing insulation wool manufactured by Terra Lana Insulation Wool [88], with an R value of 2.2 m^2K/W, between existing studs (fixed to studs and dwangs) and re gibbing the walls (see fig. 17).

Figure 17. Wool batts placed inside of the existing walls.

Figure 18. Window treatment: Drapes

Figure 19. Window treatment: Acrylic

Three different low cost window treatments were tested in this house including:

- windows being sealed using plastic film which was installed to provide a still air gap between the glass and the plastic,
- thermal curtains with pelmets (see picture 18)., and
- windows retrofitted using acrylic double glazing using a system manufactured under the trade name 'MagicSeal' [89], which allows the double panel to be removed for maintenance (see picture 19).

The floor was insulated by installing a product called 'Air-Cell', manufactured by 'Air Cell Building Insulation' [90] (see fig. 21). This product is an aluminium foil with air cells enclosed in a semi rigid plastic material. Compared with normal aluminium foil it is allegedly easier to install and has the advantage of having enclosed air cells. R values for this product installed under a suspended wooden floor with an air gap and with the heat flow outwards is claimed to be 2.2 m^2K/W [91]. Standard polyester blankets as used in the state housing upgrade programme [92] were installed over the entire ceiling, on top of existing macerated paper, giving a ceiling R value of 4.6 m^2K/W (see fig. 22).

Figure. 20.
Floor non insulated

Figure 21.
Underfloor insulation: Air-Cell

Figure. 22.
Ceiling insulation: Polyester blankets installed on top of existing macerated paper

4.2.3 Summary of Upgrades

A summary of the upgrades for both houses is shown in Table 1. The expected percentage of increase in thermal resistance after each element was upgraded is discussed in chapter 5 (5.1).

Table 1. Upgrades to elements of the building fabric – House 1 & 2

Element		Before the upgrades	After the upgrades
		Description	Description
House 1	**Walls**	Concrete block /air gap and timber frame / GIB board. No insulation.	Expanded polystyrene sheets to all external walls except wet areas
			Pink Batts in all wet areas external walls
	Windows	Single glazed wooden frame	Drapes
			Double glazed aluminium frame w argon
			Double glazed aluminium frame w argon w drapes
	Floor	Perforated Aluminium Foil with carpet	Expanded polystyrene sheets / No carpet
	Ceiling	Macerated Paper with Polyester Blankets	Macerated Paper with Polyester Blankets
House 2	**Walls**	Brick no insulation	Wool Insulation
		Weatherboard no insulation	
	Windows	Single glazed wooden frame	with drapes
			with plastic film
			with Acrylic
	Floor	Suspended wooden floor with carpet	Aluminium Foil with air cells
	Ceiling	Macerated Paper	Macerated Paper with Polyester Blankets

4.2.4 Cost of the Upgrades

The cost of the upgrades included labour costs and materials costs in NZ 2006$s. The following table 2 details the expenses incurred by the upgrades. The total cost was then divided by the total area of the building envelope to provide a cost per m^2 of upgraded area which was estimated to be around 120$/$m^2$ and approximately the same for both houses.

Table 2. Upgrade Costs– House 1 & 2

House Name	Materials	Cost *included	Purchased	Labour	Total Cost	Total Cost/m^2 **
House 1 Insulating the whole building envelope and replacement of new double glazed windows.	EPS underfloor	$600	Private Contractor	$874		
	Pink batts	$100	Contractor	$5,489		
	Formaliner	$1,886	Forman			
	Paint	$1,000*	Contractor			
	Double glass windows	$11,239	Ellisons	$3,316		
	Curtains	$2,778	Active F	$400		
	Pelmets	$334*	University of Otago			
	Paint / Hang Pelmets	$100	Bryan Smail	$400		
	Polished Floors	$3,560	Baker Flooring			
	Sealing	$800	Bryan Smail	$1,500		
	Plumbing work		Bryan Smail	$500		
	Electric work		Bryan Smail	$200		
Total House 1		$22,397		$12,679	$35,076	$123/$m^2$

House Name	Materials	Cost *included	Purchased	Labour	Total Cost	Total Cost/m² **
House 2 Insulating all the floor and ceiling Insulating walls for living room only, including cost for 3 different options for window treatment.	Air Cell	$906	Negawatt	$458		
	Polyester	$700	Bryan Smail	$786		
	Wool	$320	Bryan Smail	$3,999		
	Paint	$300*	Bryan Smail			
	Paint Windows/Ceiling	$100	Bryan Smail	$922		
	Acrylic	$934*	Designer screens			
	Curtains	$600*	Active furnishes			
	Pelmets	$100*	University of Otago			
	Paint Pelmets	$50	Bryan Smail	$150		
	Plastic Film	$50	Negawatt & CEA			
Total House 2		$4,060		$6,315	$10,375	$122/m²

** Price per m^2 refers to the total funds spent in the house divided by the total area of the building envelope. Note that House 2 had the floor and ceiling insulated for the whole house and walls for living room only. The total cost also includes the different window treatments. For a more accurate idea of the cost per m^2, the window treatment might be subtracted, which would make the upgrade cost around $NZ110/m^2.

Extra costs involved: scaffolding for House 1 as required for replacement of existing windows.

4.2.5 Our experience doing the Upgrades

Many things were learnt from the experience of upgrading the two state houses, especially practical things that could only be commented on after the upgrades were completed. Some of these are summarized below.

Figure 23. Existing wooden framed windows

Difficulty getting contractors: Around 60 letters were sent to builders in the area, inviting them to undertake the work. Advertisements were also placed in the local newspaper (Otago Daily Times) seeking expressions of interest. Only a few people responded (around 15 people actually came to view the houses). Some comments from the builders included that the cost of retrofitting was not easy to estimate and that they preferred to work in new construction. Only 12 builders actually expressed some interest in tendering for the work and of these 4 were short listed.

Retrofitting existing windows: The first intention was to retrofit existing windows by installing double glass panes into existing wooden frames. Unfortunately this was not cost effective as the market was not prepared to provide this service at a cost much lower than a new installation. It was finally found that it was more cost effective to purchase new aluminium framed double glazed windows. Even though the frames of these windows provided very poor performance in terms of heat losses, as they were not thermally broken, it was thought that some benefit was going to be achieved by improvement in air tightness.

Figure 24. New Aluminium framed windows

This decision was made on a cost basis only. No consideration was given to the embodied energy (and environmental impact) of both options, as the new aluminium window would have had considerably more embodied energy content than a retrofit option. Foam was used around the windows frames as seen in fig. 25 to ensure good insulation continuity between the frames and the wall insulation.

Testing causing moisture removal: After heating the houses during the testing for longer periods of time and to higher temperatures than achieved under normal occupation, the house dried out. This effect, unfortunately, caused the wood floor to shrink, leaving gaps between the wood battens. Gaps were filled with a flexible product manufactured by 'Sika'. This product is usually used in marine applications to allow expansion and contraction of wood decking on boats. The installation of this product was problematic as it was very labour intensive. Similar problems were reported while doing a similar study in the UK [93]. These researchers found that after finishing the heating tests, visible cracks appeared in the corners of the rooms. They attributed the cracking to the abnormal amount of heating applied to the dwelling during the testing.

Figure 25. Foam around window seal in new windows

Figure 26. Wooden floor showing existing gaps

Figure 27. Polished floor with filled gaps

Drapes: Drapes were initially thought to be an economic way to improve thermal performance of windows. Options were normal drapes, roman drapes, or rolling drapes. While normal drapes require more fabric and work better if installed with pelmets, the second two options require less fabric and no pelmets but more skill in the manufacturing process. Unfortunately due to high labour costs none of the available options were found to be economically attractive in Dunedin. Curtains were made to cover the entire width of each window and falling until the floor with pelmets to prevent heat from escaping through the top. Ideally the gap between the drapes and the window should be as small as possible to reduce air movement (heat loss by convection), this was not the case as the retrofitted windows sills were wider than normal ones. External shutters, as used in many other places in the world, were also considered but again this option was outside the comfort zone of suppliers in NZ and a suitable contractor was not found to offer such a product.

Finally pelmets were made for each window. When fitting these pelmets it was found that some of the walls were not straight. This meant that a small air gap was required to be filled for better performance.

Retrofitting the walls: Insulating the walls by installing the product Formaliner was not found to be easy by the contractor. Cutting this material to fit each area required more time than anticipated. It was suggested by the contractor that in most cases it would have been easier to install bulk insulation in the cavity and re- GIB the walls, (as was done in the wet areas). The advantages of using the Formaliner were that an extra layer was provided on top of the existing wall giving added extra surface resistance layers and with the additional advantage of avoiding thermal bridging due to the studs and dwangs.

Figure 28. Fitting wall insulation (Formaliner)

Another complication of this system, however, was having to match the in-situ angles of an old established house. These angles were not always 90º and required more time and skill.

Although the expanded polystyrene has higher embodied energy when compared with other soft bulk insulation materials (20.6kWh/m^2 vs. 11.14kWh/m^2 for 50 mm thickness), it is a rigid material that it is thought to last longer as it will not settle, retaining its thermal properties for longer periods of time. Unfortunately the Formaliner did not come thicker and only 55 mm of Expanded polystyrene sheets (EPS) could be installed.

Insulating under the floor: The EPS panels were found to be easy to install under the floor, however, some of them had to be readjusted and fixed with nails after becoming loose. See fig. 29.

According to the contractor, the installation of Air-cell was much easier than regular aluminium foil because it was easier to manipulate and fix to the structure. See fig. 30.

Removing the carpet and the vinyl was not easy in some areas, requiring extra time to be spent for this task.

When the carpet was removed, air ingress increased, as the carpet had slowed the air flow. The gaps thus needed to be filled using a sealing compound.

Testing for Air infiltration: By doing the blower door test and walking around the house while the house was being pressurized we were able to identify air leakage areas. These included corners (especially inside wardrobes and along cornices and skirting). Also some (but not all) of the wooden framed windows were found to be very leaky. Some of these areas were sealed before the final test to reduce losses though such gaps.

Community approach: An open day having both houses participating in a Trans-Tasman event called 'Sustainable House Day' [94] offered a chance for the community to visit the houses and make contact the people involved in the project, including the builder. Many visitors interested in retrofitting their own house asked questions regarding the performance and practicality of each upgrade option. From that event it was evident that there is a need in this area to provide advice on how to achieve warmth in existing houses in a cost effect manner.

Alternative window treatments: Acrylic sheets were attached using magnetic strips to existing window panes in House 2., as shown in fig. 32. It was noted that after several months some of the magnetic strips did not perform as expected, causing air infiltration between the acrylic and the windows which in turn caused condensation in the air gap. However, as the panes were not fixed, they could easily be wiped avoiding major problems. Overall, however, it was thought that the magnetic strips did not provide a sufficiently sealed air gap for good thermal performance.

Figure 29. EPS panels under the floor.

Figure 30. Air cell under floor insulation.

Figure 31. Expanded Polystyrene Sheets

Figure 32. Acrylic Sheets

CHAPTER 5 : RESULTS

5.1 Thermal Modelling: manual calculation (heat losses)

The effective thermal resistance of the test houses was calculated by taking into account the total heat losses by conduction (through the building envelope materials) and by infiltration (air ingress).

5.1.1 Heat Losses: reduction expected due to the upgrades

The thermal resistance of House 1 was modelled over 3 stages of existing historical upgrade identified (H1-A, B and C). Then, this house was upgraded at 7 different levels with tests being performed at each level (H1-1 to 7). House 2 had two stages of existing historical upgrade (H2-A and B). This house was then upgraded with a combination of different materials in 10 separate stages with each stage being tested (H2-1 to 10).

All the different stages were modelled to account for heat loss reduction due to the respective upgrade. Upgrades installed in both houses are shown in the following tables 3 and 4.

Table 3. Upgrades for House 1

House 1: 118		Stage Test	Date	Description	Upgrades **Ceiling**	 **Walls**	 **Windows**	 **Floor**	 Carpet
Upgrades	Historical Upgrades ESTIMATED	H1-A	`60	Original House	None	None	None	None	Yes
		H1-B	'70-`80	Ceiling 70's retrofit	Macerated paper	None	None	None	Yes
		H1-C	2004	Ceiling HNZC upgrade	& Polyester blankets	None	None	None	Yes
	Proposed Upgrades TESTED	H1-1	2004	Standard HNSC package	& Polyester Blankets	None	None	Aluminium foil	Yes
		H1-2	2006	Drapes	& Polyester Blankets	None	Drapes with pelmets	Aluminium foil	Yes
		H1-3	2006	Removed unerfloor and carpet	Macerated paper & Polyester Blankets	None	None	None	No
		H1-4	2006	Underfloor EPS	Macerated paper & Polyester Blankets	None	None	Expanded polystyrene	No
		H1-5	2006	New double glass windows	Macerated paper & Polyester Blankets	None	Double glass	Expanded polystyrene	No
		H1-6	2006	Wall insulation	& Polyester Blankets	polystyrene & Pink batts	Double glass	Expanded polystyrene	No
		H1-7	2006	Polished floors and drapes	& Polyester Blankets	polystyrene & Pink batts	Double glass	Expanded polystyrene	No
m²	285.45				87.90	76.65	33.00	87.90	
%	100%				31%	27%	12%	31%	

Table 4. Upgrades for House 2

House 2: 83		Stage Test	Date	Description	Upgrades **Ceiling**	 **Walls**	 **Windows**	 **Floor**	 Carpet
Upgrades	Historical	H2-A	`60	House as originally	None	None	None	None	Yes
	Proposed Upgrades TESTED	H2-1	2006	Ceiling 70's retrofit	Macerated paper	None	None	None	Yes
		H2-2	2006	Plastic Film on windows	Macerated paper	None	Thin plastic film	None	Yes
		H2-3	2006	Drapes and palmetd	Macerated paper	None	Drapes	None	Yes
		H2-4	2006	Undefloor insulation	Macerated paper	None	Drapes	Radiant barrier on bubble wrap	Yes
		H2-5	2006	Wall insulation	Macerated paper	Wool	None	Radiant barrier on bubble wrap	Yes
		H2-6	2006	Ceiling insulation	Macerated paper & Polyester	Wool	None	Radiant barrier on bubble wrap	Yes
		H2-7	2006	All + plexiglass on windows	Macerated paper & Polyester	Wool	Plexiglass with 10mm air gap	Radiant barrier on bubble wrap	Yes
		H2-8	2006	All + duets on windows	Macerated paper & Polyester	Wool	Window Shade	Radiant barrier on bubble wrap	Yes
		H2-9	2006	All + drapes	Macerated paper & Polyester	Wool	Drapes	Radiant barrier on bubble wrap	Yes
		H2-10	2006	All + plastic film on windows	Macerated paper & Polyester	Wool	Thin plastic film	Radiant barrier on bubble wrap	Yes
m²	85.47				17.25	44.26	6.72	17.25	
%	100%				20%	52%	8%	20%	

5.1.2 House 1: modelling by calculation

Heat losses for House 1 were calculated, including appropriate allowances for thermal bridging for the various upgrade stages.

Fig. 33 shows the results of heat loss reduction at each stage though the addition of different components to the building fabric. As can be seen the highest impact is seen after insulating the walls and replacing the windows. Calculated heat losses were reduced by 42% after the house was fully upgraded.

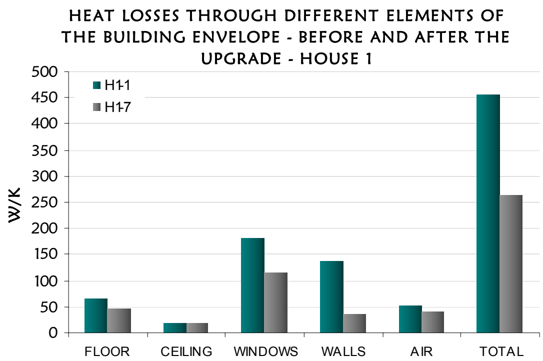


Figure 33. Modelling House 1 - Heat Losses through different element of the building envelope – Test H1-1 vs. H1-7

The overall percentage of heat loss for each component of the building envelope for different stages at House 1 is shown in fig. 34; the arrows represent how much of the total heat energy was going through each element at each stage. The three graphs represent the house as originally built, the HNZC upgraded package, and the fully upgraded house. Insulating the ceiling was a good thing to do in the first place as almost one third of the energy escaped through the ceiling of the originally un-insulated house. After the ceiling was insulated, it can be seen that more than 50% of heat loss occurred through walls and windows and only 4% of the total losses occurred through the ceiling. According to the modelling, total reductions of 38% in heat loss occurred after the 1970s upgrade and HNZC upgrade package. A further 42% reduction would be expected after this house was fully upgraded (from 457 W/K to 263 W/K) for a 88 m^2 house. A total reduction in heat loss from original to fully upgraded was expected to be around 65%.

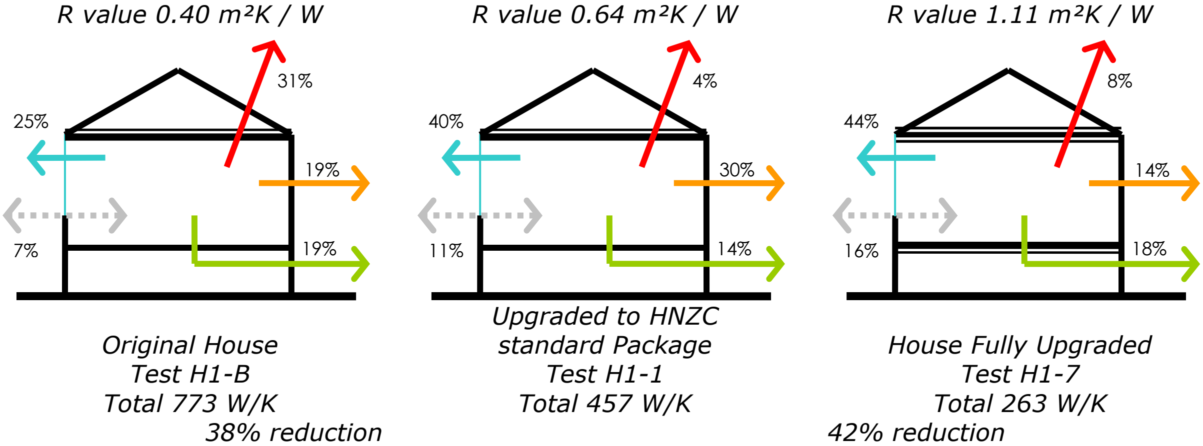


Figure 34. House 1: Percentage of heat losses through the building envelope

As a result of a reduction in heat losses through the various components of the building fabric and air infiltration, the lumped resistance of the building envelope is expected to increase 0.64 m²K/W for the house before the upgrade to 1.11 m²K/W after this house was fully upgraded, with an increase in R value of 58%.

Total heat losses *by conduction* for each element at each stage are shown in fig. 35 together with the implied increase in R value. Each step of improvement can be identified as a reduction in heat losses for the specific element. The R value was expected to increase from 0.72 to 1.32 m²K/W (H1-1 to H1-7).

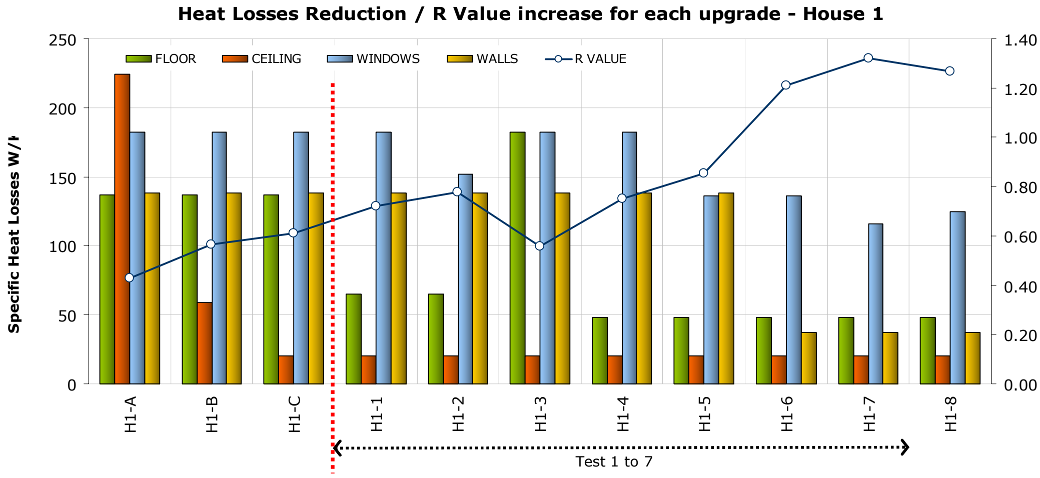


Figure 35. Heat Losses by conduction reduction and R Value increase for each upgrade in House 1

5.1.3 House 2: modelling by calculation

The lumped R values were calculated for the living room of House 1, again including appropriate allowances for thermal bridging for the various upgrade stages.

Fig. 36 shows the expected heat loss reduction after the upgrades. Because of the large wall area in the room (i.e. a higher proportion of wall area to volume in the living area compared to the whole house), the highest impact in reduction of heat losses is seen after insulating the walls. A significant reduction was also expected to be found after insulating the floor and the ceiling, which had not been upgraded with the HNZC upgrade package.

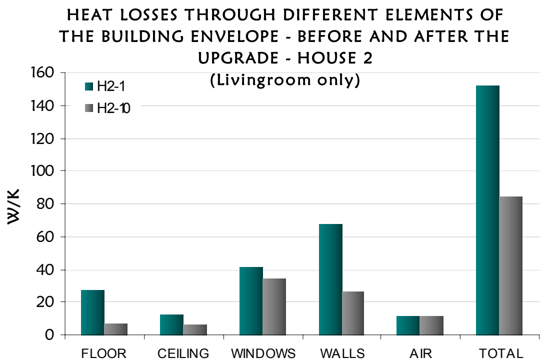
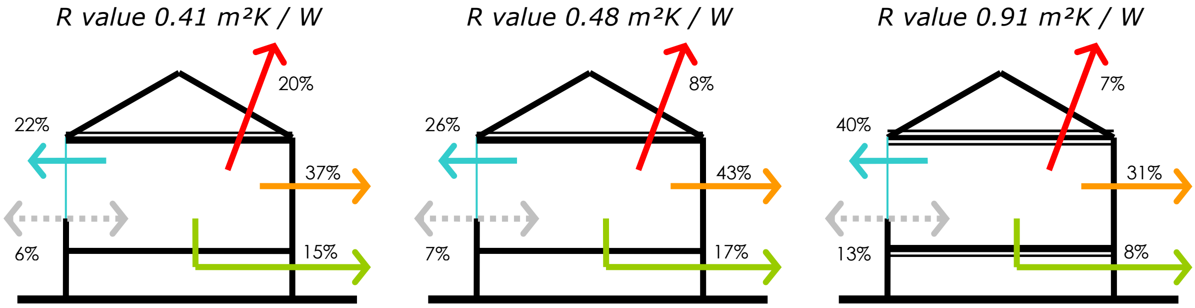


Figure 36. Modelling House 2 – Heat Losses through different elements of the building envelope – Test H2-1 vs. H2-10



Original Living room Configuration H2-A (As built) Total 184 W/K
Living room Upgraded 70s retrofit Configuration H2-B (Before) Total 159 W/K
Living room Fully Upgraded Configuration H2-10 (After) Total 84 W/K
14% reduction
47% reduction

Figure 37. House 2: Percentage of heat losses through the building envelope – Living room only

As it can be seen in fig. 37 only a 14% reduction occurred after insulating the ceiling in the previous 1970s upgrade. A further 47% was expected to be achieved after all upgrades were done in the living room of this house. In this case around 70% of the losses occur through the walls and windows. Thus most of the reduction of heat losses occurred by insulating the walls.

The total heat losses by conduction for each element at each stage are shown in fig. 38 together with the consequent increase in R value. Each step of improvement can be identified as a reduction in heat losses for the specific element. As expected the highest impact is shown when insulating the walls, when the R value increases from 0.51 m²K/W to 1.04 m²K/W (H2-1 to H2-10).

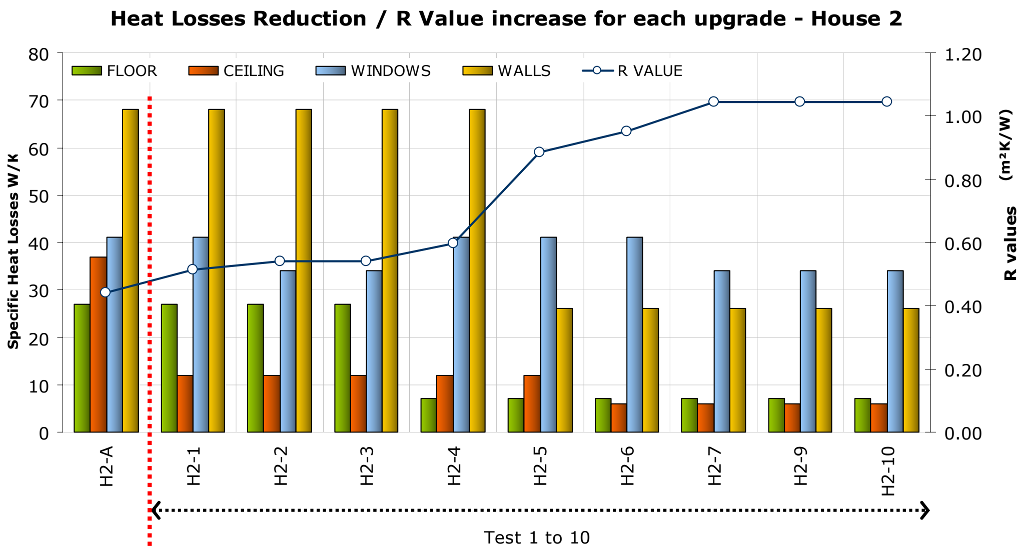


Figure 38. Heat Losses by conduction reduction and R Value increase for each upgrade in House 2

5.1.4 Summary

Both houses had an original calculated R value of between 0.40 m²K/W and 0.41 m²K/W for non insulated houses. After reducing heat losses through different upgrades, an increase in the thermal resistance of the building fabric was expected for both houses after the upgrades. House 1 was expected to achieve a final effective R value of 1.11 m²K/W after the whole house was upgraded, while House 2 was expected to achieve an effective R value of 0.91 m²K/W in the living room only. This represents a factor of 2.7 improvement for House 1 and 2.2 m²K/W for House 2.

5.2 Experimental thermal testing (heat losses)

5.2.1 Experimental Design

The heat loss for a house can be measured by introducing a known flow of heat to a house and measuring the temperature increase achieved at the equilibrium point. At this time the heat gain from the heater must equal the total heat loss.

When a house is heated, at first the heat energy goes into increasing the temperature of the building mass and air inside the building. Eventually a steady state is reached where heat loss to the outside is balanced by heat added to the house. If the outside temperature is stable and there are no other gains then, the inside temperature will stabilise.

As sunlight can contribute to the net energy gain of a house, the experiment must be conducted at night when there are no solar gains.

For each building retrofit, the house was heated for 16 to 20 hours, reaching equilibrium (where possible) in the morning before the sun rose. The internal and external temperatures were monitored so that the equilibrium condition could be verified.

Data Collection

The indoor temperatures were continuously measured in each room of the house using HOBO data loggers. Outside temperature and humidity was monitored with a Vaisala HMP45 probe. Heater power was measured with calibrated power meters, and logged using 'TinyTag' pulse counters.

The data was stored, after correction using the calibration curves, in a postgres SQL database, and loaded into the R statistical program for charting and analysis.

Two typical experimental runs are shown below as time series of temperatures, power, and external wind speed and direction. The horizontal axis is time, measured in hours. Data points were recorded every five minutes. The graphs are further explained below.

The observational data was subject to some real world disturbances. Any sudden changes in ambient temperature, in particular, would give rise to non equilibrium conditions making interpretation difficult. An example is seen in fig. 39 which shows a disturbance which caused a reduction in the net temperature difference. In this case the net temperature difference did not stabilise over the observation period, as there was insufficient time for the thermal mass of the system to come into equilibrium.

Experimental runs which did not produce a reasonable equilibrium were excluded from the data set.

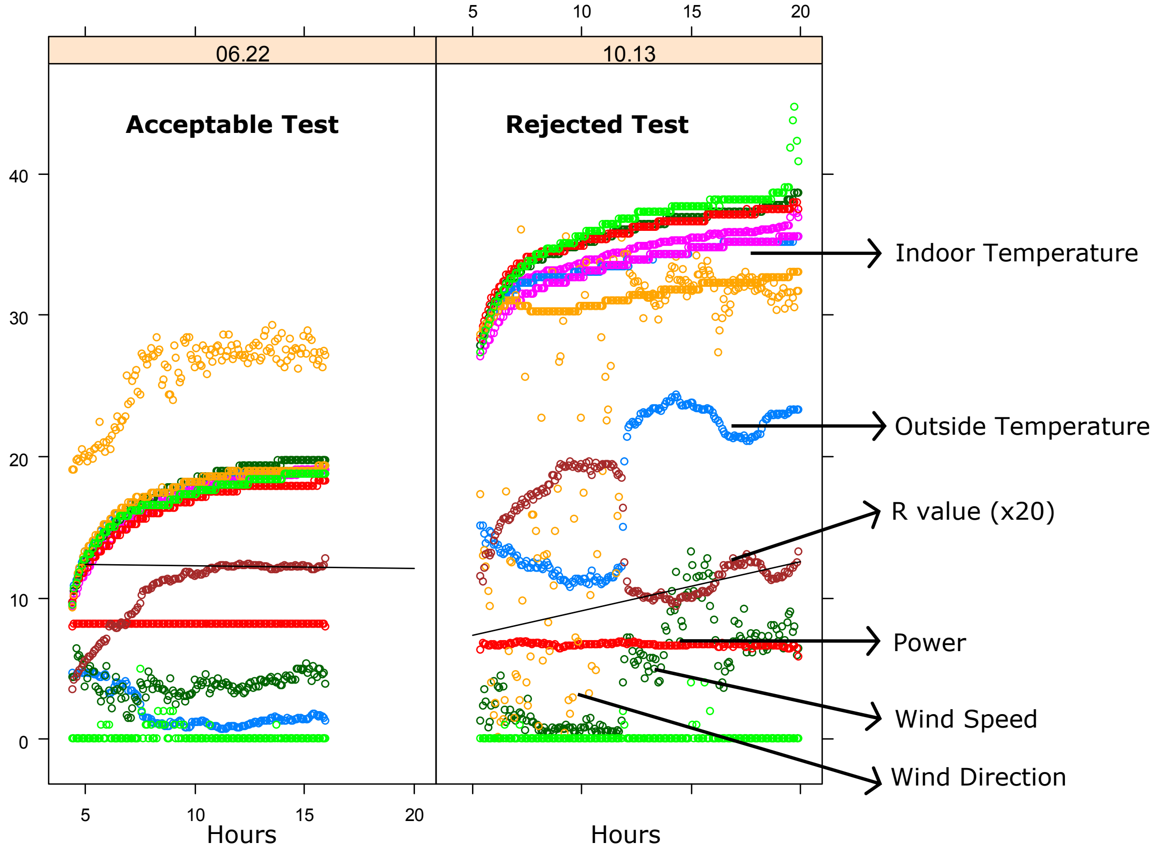


Figure 39. Test results from 2 days: One accepted and one rejected

As a further example of the data selection process, fig. 39 shows the data collected and analysed for 2 different days. The first day (22/June/06, on the left) the test was considered to be acceptable, but the second day (13/October/06, on the right) the test was rejected as explained above.

The horizontal axis shows the duration of the test in hours. Tests usually started at 4:00 pm each day and ran for around 16-20 hours. The vertical axis shows several variables in different units, depending on the data measured. The top purple line shows the internal temperature in the house. The bottom blue line indicates the outside temperature.

The brown line in the middle of the chart is the R-value multiplied by 20, calculated at each 5 minute interval. The R value has been scaled to fit on the chart by multiplying by 20. The straight line is a fit to the R value for the last 4 hours of the test. A near horizontal fit implies the net temperature difference reaches a suitable equilibrium condition. When this line indicates that the temperature difference is changing less than 1/3 of a degree per hour, the temperatures were assumed to be stable, and the test was accepted. This is the case for the test on the left (i.e. test 06.22). The test on the right (10.13) did not reach equilibrium and so was rejected.

5.2.2 Uncertainty

Fig. 36 (06.22) shows an acceptable test result. After the inside temperature reached steady state, the net temperature difference was used during the last two hours of the testing period to calculate the lumped R value.

Accurately measuring the heat loss attributable to each upgrade was just at the limits of measurement. An ANOVA test was used to investigate how the variance in heat loss measurements could be attributed to the upgrades. This test indicated that the upgrades did reduce heat loss, with a high level of confidence (95% and higher). The heat loss for each upgrade stage is shown in the results section, with the statistical uncertainty calculated from the standard deviations and the standard t-dist for the number of observations.

As the differences between the R values for the individual upgrade changes were small, the differences required further statistical resolving power. A Tukey's test was used to examine the statistical significance of the changes in R value between each stage. This test, however, indicated that only some of the differences between tests were statistically significant. The cases where the differences are statistically significant according to this test are indicated where appropriate.

Results

Results of our measurements for both houses are presented below. House 1 gave the following results:

Table 5. Test Results for House 1

HOUSE 1		**Tested**	**Accepted**	**Heat Losses**		**Air Leakage at 50 Pascals**	
TEST	**DESCRIPTON**	Days		W/K	Error	m^3/hr	Error
H1-1	Original	5	5	438	± 83	3511	± 1053
H1-2	Drapes	7	7	409	± 41	3511	± 1053
H1-3	No carpet and undefloor insulation	4	4	460	± 25	5058	± 1517
H1-4	EPS Underfloor insulation	10	10	416	± 36	5981	± 1794
H1-5	Double Glazing	12	12	401	± 17	5143	± 1543
H1-6	Walls Insulation	8	5	350	± 23	4437	± 1331
H1-7	Drapes + Double Glazing	4	3	296	± 20	3863	± 1159

Table 5 shows the total heat loss reduction with each successive upgrade, and the air leakage at 50 Pa for each upgrade step (last two columns). The total heat loss of the original house was 438W/K. The use of drapes reduced the heat loss to 409 W/K. Removing the underfloor insulation and carpet increased heat loss, in part because of the increase in air leakage measured. Adding EPS underfloor insulation restored the heat loss to a value similar to the original heat loss. Double glazing reduced the heat loss yet further. As can be seen, the most significant heat loss reduction was achieved by insulating the walls.

Table 6. Test Results for House 1

HOUSE 1	**Effective - Measured**		**ACH**	**Heat Losses**				**Conduction Only**	
	U value	R value		Air infiltration		Conduction		U value	R value
TEST	W/m²K	m^2K/W	ACH	W/K		W/K		W/m²K	m^2K/W
H1-1	1.5	0.67	0.71	58	± 17	380	± 85	1.3	0.77
H1-2	1.4	0.71	0.71	58	± 17	351	± 44	1.2	0.83
H1-3	1.6	0.63	1.03	83	± 25	377	± 35	1.3	0.77
H1-4	1.4	0.70	1.21	99	± 30	318	± 47	1.1	0.92
H1-5	1.4	0.73	1.04	85	± 25	316	± 31	1.1	0.92
H1-6	1.2	0.83	0.90	73	± 22	277	± 32	0.9	1.05
H1-7	1.0	0.99	0.78	64	± 19	232	± 28	0.8	1.26

The difficulty of working with changing environmental conditions meant that the accuracy of this test method has not always allowed a statistically significant comparison of the R value differences for each test and thus level of upgrade.

House 2 had the following results:

Table 7. Test Results for House 2

HOUSE 2		**Tested**	**Accepted**	**Heat Losses**		**Air Leakage at 50 Pascals**	
TEST	**DESCRIPTON**	Days		W/K	Error	m^3/hr	Error
H2-1	Ceiling Upgrade(70 retrofit)	12	11	164	± 7	949	± 285
H2-2	Plastic film in windows	6	6	135	± 14	761	± 228
H2-3	Drapes	7	6	138	± 13	949	± 285
H2-4	Underfloor insulation + drapes	4	4	130	± 11	1149	± 345
H2-5	Walls insulation	10	8	90	± 8	1536	± 461
H2-6	Ceiling insulation	20	11	84	± 8	1536	± 461
H2-7	Fully insulated + plexiglass	4	1	75	± 13		
H2-8	Fully insulated + blinds	3	1				
H2-9	Fully insulated + Drapes	5	4	70	± 5	1536	± 461
H2-10	Fully insulated + window plastic film	5	3	75	± 13	1536	± 461

The table above shows the total heat loss reduction with each successive upgrade, and the air leakage at 50 Pa for each upgrade step (top table, last two columns). The total heat loss of the original lounge was 164 W/K. Insulation upgrades reduced this to 84 W/K, with the most significant steps being the addition of drapes, and insulation of the walls. The use of drapes or window plastic after insulation further reduced heat loss to an identical (and statistically significant) 72 W/K.

Unexpectedly, the air infiltration rose dramatically after the insulation of the walls. This was believed to be the result of significant air gaps introduced during the re-Gibbing process. Gaps between the Gib board and the floor (hidden behind the skirting) were observed after the end of testing. These gaps would have allowed the free passage of air into the wall cavity. This observation clearly shows that considerable care need to be taken to undertake the upgrade if a positive result is required.

Table 8. Test Results for House 2

HOUSE 2	**Effective - Measured**		**ACH**	**Heat Losses**				**Conduction Only**	
	U value	R value		Air infiltration		Conduction		U value	R value
TEST	W/m²K	m²K/W	ACH	W/K		W/K		W/m²K	m²K/W
H2-1	2.1	0.47	0.74	16	± 5	148	± 8	1.9	0.52
H2-2	1.8	0.56	0.59	13	± 4	123	± 14	1.6	0.62
H2-3	1.8	0.55	0.74	16	± 5	123	± 14	1.6	0.62
H2-4	1.7	0.59	0.89	19	± 6	111	± 13	1.5	0.69
H2-5	1.2	0.84	1.19	25	± 8	65	± 11	0.9	1.17
H2-6	1.1	0.90	1.19	25	± 8	59	± 11	0.8	1.29
H2-9	0.9	1.09	1.19	25	± 8	44	± 9	0.6	1.72
H2-10	1.0	1.02	1.19	25	± 8	49	± 15	0.6	1.55

The Tukey's test indicated that some measurements were statistically significant. The use of drapes or window plastic reduced heat loss by around 25 W/K, which is equivalent to a window thermal conductivity reduction of 3.8 W/m²K. This result is better than the reduction expected for aluminium framed double glazed windows, and is similar to the reduction in heat loss if double glazed windows with wooden frames had been used, but at much less cost.

Table 9. Measured Component Heat Loss

Component	**Heat Loss Reduction**	**Uncertainty**	**Area**	**Equivalent U-value of component**	**Uncertainty**
	W/K		m²	W/m²K	
Drapes	25	± 17	6.72	3.8	± 3
Window Plastic	28	± 17	6.72	4.2	± 3
Wool Walls	39	± 20	44.26	0.9	± 0

The wool walls reduced heat loss for the entire room by 39W/K, giving a thermal conductivity reduction of 0.9 W/m²K as can be seen in Table 9.

5.2.3 Comparison between Calculated and observed heat losses

Differences between expected and monitored heat losses are shown in the following tables 10 and 11. Some of the tests were not taken into consideration as errors were too high to allow a valid comparison. Within the margin of error, the heat loss of the original house (H1-1) was within that predicted by theory. However the performance of the floor insulation may be less than that calculated using the given R values for the material. The heat loss expected when the carpet and underfloor insulation was removed was much less than expected. The difference cannot be explained by experimental uncertainties alone.

Table 10. Results compared House 1: Expected vs. Observed

H1	**118**	**Heat Losses**				
		Expected		**Tested**		**Difference**
Test	**Description**	W/K		W/K		W/K
H1-1	Original	457	± 61	438	± 83	-19
H1-2	Drapes	427	± 62	409	± 41	-18
H1-3	No carpet and undefloor insulation	590	± 89	460	± 25	-130
H1-4	EPS Underfloor insulation	456	± 66	416	± 36	-40
H1-5	Double Glazing	394	± 68	401	± 17	7
H1-6	Walls Insulation	293	± 46	350	± 23	57
H1-7	Drapes + Double Glazing	263	± 51	296	± 20	33

Table 11. Results compared House 2: Expected vs. Observed

H2	**83**	**Heat Losses**				
		Expected		**Tested**		**Difference**
Test	**Description**	**W/K**		**W/K**		**W/K**
H2-1	Ceiling Upgrade(70 retrofit)	159	± 18	164	± 7	5
H2-2	Plastic film in windows	152	± 18	135	± 14	-17
H2-3	Drapes	152	± 18	138	± 13	-14
H2-4	Underfloor insulation and drapes	139	± 17	130	± 11	-9
H2-5	Walls insulation	97	± 14	90	± 8	-7
H2-6	Ceiling insulation	91	± 14	84	± 8	-7
H2-7	Fully insulated + plexiglass	84	± 13	75	± 13	-9
H2-8	Fully insulated + blinds					
H2-9	Fully insulated + Drapes	84	± 13	70	± 5	-14
H2-10	Fully insulated + window plastic film	84	± 13	75	± 13	-9

Expected and monitored heat losses are compared in fig 40. Also of interest was how much less power (1-2 kW) was required to heat the lounge of House 2 compared with the entire of House 1 (8-9 kW).

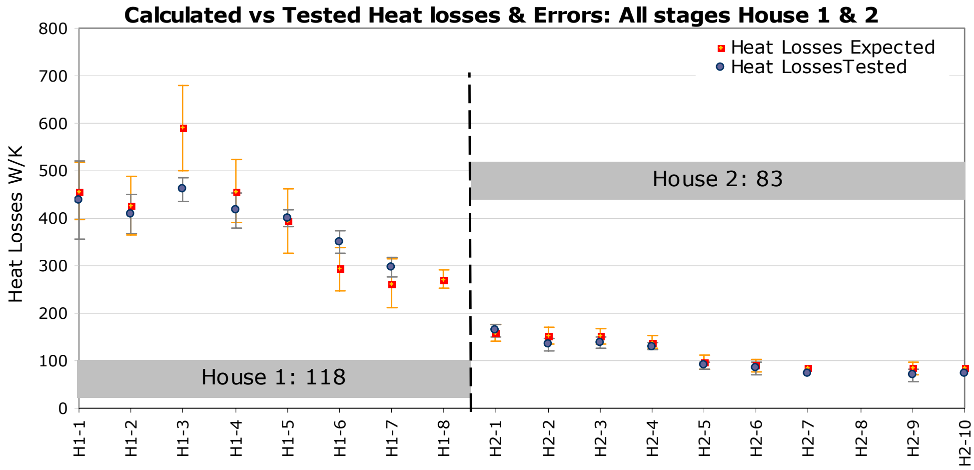


Figure 40. Heat Losses Expected vs. Tested (House 1 and House 2)

5.2.4 Comparison with NZ Building Code Requirements

House 1 was modelled to meet minimum NZ Building Code Requirements. Results are shown in Table 12 and give us total R values of 0.69 m^2K/W for 1977 regulation, 0.79 m^2K/W or post 1996 regulation and expected 0.91 m^2K/W after double glass is expected to becomes compulsory for new buildings in the South Island in 2007. The table compares these values with the ones obtained in our experiment. For the purpose of this calculation we have compared House 1, test 6 which is not the final test as this one doesn't include drapes as in the final test. As can be seen at this stage, an effective tested R value of 0.83 m^2K/W was obtained which was lower than expected.

Table 12. Lumped R value for House 1 for building code requirements

Summary		R VALUES - ZONE 3										
Regulatioons		BEFORE '77 ESTIMATED	CODE 1977	EMAN 2006*		CODE SOLID POST '96	RECOMMENDED		CODE LIGHT POST '96	RECOMMENDED		CODE LIGHT 07
Element	m^2	NONE	MINIMUM	EXPECTED	TESTED	MINIMUM	BETTER	BEST	MINIMUM	BETTER	BEST	MINIMUM
CEILING	89.50	0.40	1.9	4.48		3.00	3.5	4.6	2.50	3.5	4.6	2.50
GLASS	32.60	0.19	0.19	0.26		0.19	0.26	0.26	0.19	0.26	0.26	0.26
DOOR	4.00	0.40	0.40	0.40		0.40	0.40	0.40	0.40	0.40	0.40	0.40
WALLS	76.10	0.55	1.5	2.06		1.00	1.6	1.9	1.90	1.6	1.9	1.90
FLOOR	89.50	0.65	0.9	1.86		1.30	1.9	3.1	1.30	1.9	3.1	1.30
LUMPED R V		**0.40**	**0.69**	**1.03**	**0.83**	**0.73**	**0.98**	**1.10**	**0.79**	**0.98**	**1.10**	**0.91**

* Values are for House 1 - Test 6 (H1-6) Fully insulated tested with NO drapes, Final Test gave higher R values.

The following graph shows R values (m^2K/W) expected and tested for House 1 together with the minimum required for each one of the Building Code requirements and recommended for Zone 3.

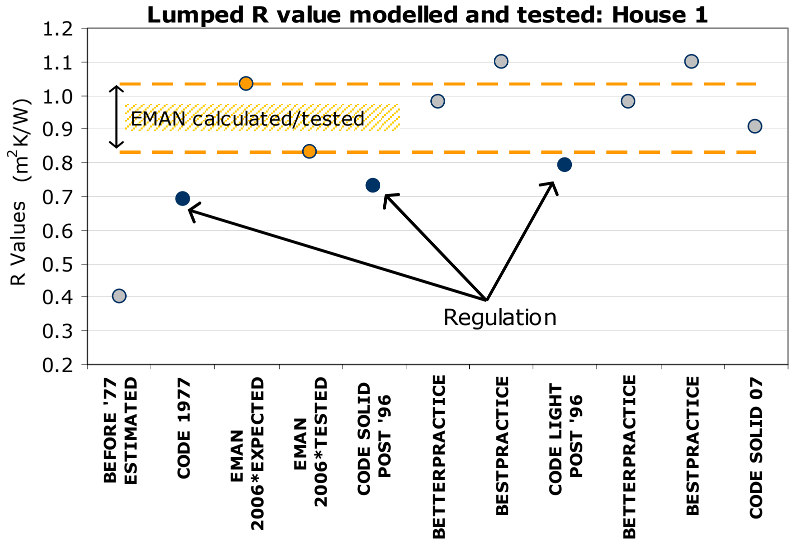


Figure 41. Lumped R value for House 1 for modelled for different building code requirements

5.3 Annual heating energy required using ALF

Once the houses thermal behaviour was understood, we proceeded to model the houses using ALF3. As identified in our previous report HNZC [1], occupants usually do not heat the house over a 24 hour period and do not usually heat the entire house. What we can suggest from our previous study is that the amount of energy that HNZC tenants provide for space heating is around 3000kWh/year and that this heating is mainly provided to living areas in the winter during the evening.

This section reports on the heating requirements (kWh) of net energy required for space heating. Heating efficiencies and costs are dealt with in the following section and will be used to report on the difference between heating systems and sources.

5.3.1 House 1 (118): Energy Requirements

As originally built without any insulation (H1-A), the house required 5000 kWh per year to heat to 16ºC during the evening. After the current set of upgrades, only 2500 kWh of net heating energy in needed annually for the same temperature and schedule.

After applying additional wall and floor insulation, and double glazing with drapes, the house can be heated for 700 kWh a year for the same schedule. The average 3000 kWh per year energy use in state houses will allow for all day (7am-11pm) heating to 16ºC. The annual energy requirements for all heating schedules and set points for each upgrade configuration can be seen in fig. 42.

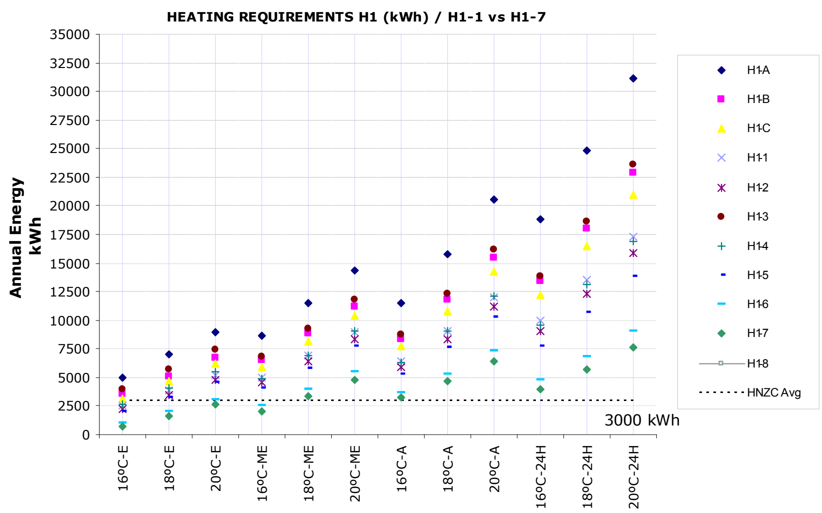


Figure 42. Heating Requirement for House 1, H1-A to H1-7

Fig. 43 compares differences in energy required for H1-1 vs H1-7. The dotted lines represent the heating requirements for the house before the upgrades, and the continuous lines are for after the upgrades. As can be seen, similar energy is required to heat the whole house for the evening schedule only, before the upgrade, as is needed to heat the same house for the whole day after the upgrade (same indoor temperature). It can also be seen that it requires less energy to heat the whole house for 24 hours to 18ºC after the upgrade (yellow continuous line) as it does to heat the same house before the upgrade to 20ºC during evenings only (red dotted line).

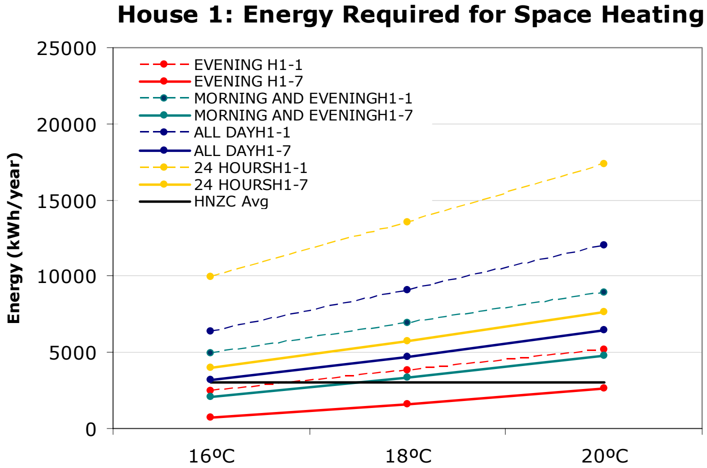


Figure *43. Energy requirements for space heating H1-1 vs H1-7 for all heating schedules and set points*

5.3.2 House 2: Energy Requirements

House 2 was modelled for heating the living room only. The house was modelled as originally found with no insulation (except for the macerated paper in the ceiling) with annual heating requirements of 1093 kWh to heat the living room to 16ºC during the evening and 2379 kWh to heat during the whole day to 16ºC.

The energy requirements for all heating schedules and set points for each configuration can be seen in fig. 44. The percentage of energy reduction of the originally built room with the fully upgraded living room in 2006 (H2-A vs H2-10) is shown with a blue line and percent reductions before and after the upgrades (H2-1 vs H2-10) is in an orange line. As can be seen, the amount of savings ranges between 55% and 61% depending on the heating schedule and set point chosen.

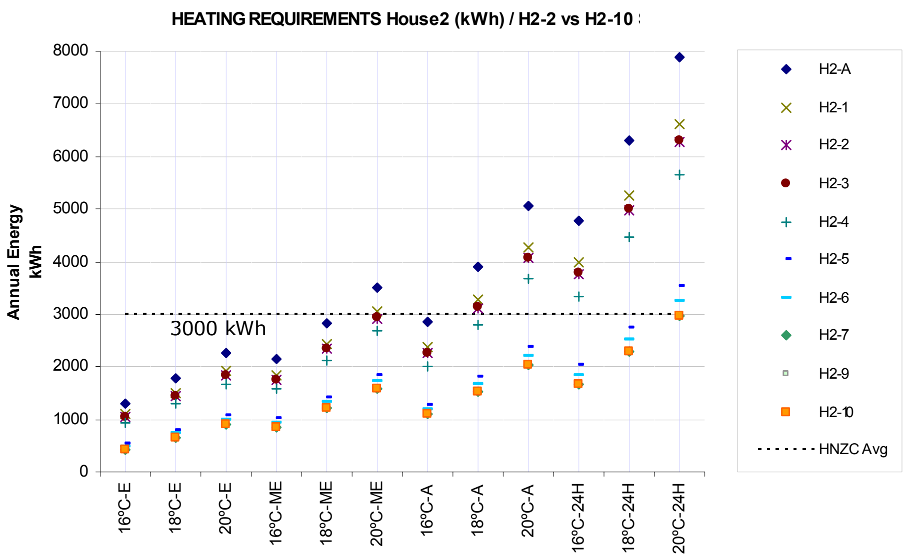


Figure 44. Heating requirement for House 2 (living room only), H2-A to H2-10

Fig. 45 shows a comparison of energy required for H2-1 vs H2-10 for the different heating schedules and set points. Dotted lines represent the heating requirements for the house before the upgrades, and continuous lines are for after the upgrades. As can be seen, similar energy is required to heat the living room for an evening schedule before the upgrade as it is to heat the same area for the whole day after the upgrade to the same temperature.

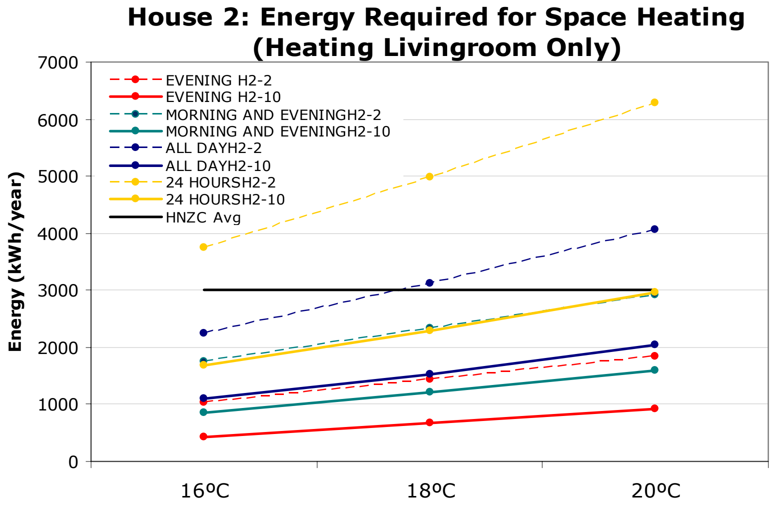


Figure 45. Energy requirements for space heating H2-1 vs. H2-10 (living room only) for all heating schedules and set points

CHAPTER 6 : Cost Benefit Analysis

An energy inefficient house has many possible upgrade paths. Thus a decision has to be made as to which upgrade should be undertaken first, in order to gain the most benefit for the least possible cost and least environmental impact. Single glazed windows can be replaced with double glazing, ceilings insulated, new windows and conservatories added, walls insulated, or new heating systems installed. Each upgrade may reduce heat losses, increase solar gains, increase heating efficiency, change the size of the heated area, or use a different fuel, but they will come at a cost both financial and in terms of embodied energy and carbon emissions.

This chapter compares the impact of different upgrade options and suggests an optimum upgrade path for a typical state house that has been already upgraded with the standard HNZC upgrade package. A model has been developed to help visualize the immediate effect of selected interventions and also their impact into the future.

Possible upgrade options have been compared and ranked to suggest most economic options to be chosen at each step. To do this, the value of energy saved over a life time has been compared with initial cost of investment. This is similar to a technique described in Gorgolewski 1995 [95]. In addition, the reduction (or increase) in recurrent CO_2 emissions (CO_2 emission due to burning fuels for space heating) have also been considered when deciding on an optimal upgrade path.

Some of the variables in the model can be chosen by the occupant (for example, set point temperature, heating areas, etc.) while others require more intervention and thus need to be undertaken by the house owner or builder (i.e. house construction, heater placement, and insulation, etc.). In addition some other variables can not be modified without switching houses (i.e. location, topography, etc.).

Our model allows us to explore the effect of a combination of different input variables. For the purpose of this report, only a selection of results are presented, these include: exploring the effects of the upgrades as per our experimental results and exploring different heating options. A combination of upgrade options is presented. The effects of other configurations could be explored using this model in future studies.

To estimate lifetime costs and CO_2 emissions, a time frame for the lifetime of the building must be specified. Some upgrades will last as long as the building (i.e. insulating the walls) while others will need to be replaced more often (i.e. heating appliances). Additionally it is customary to discount future costs via a specified discount rate. CO_2 emissions are not discounted. In this cost benefit analysis, a discount rate of 5% is used and a 10 year lifespan is used as it is estimated that after this period of time some of the upgrades would need either maintenance or replacement.

Further work needs to be done if longer periods of time need to be analysed in order to incorporate maintenance and replacement of appliances such as space heaters. Also further research could investigate a range of house styles and regions and integrate the effect of CO_2 emissions due to the production of upgrade materials.

In addition we can identify different priorities for the different players. Tenants will want to minimise annual energy costs while environmental concerns would want to minimise energy use and annual CO_2 emissions. From the range of possibilities available, we can meet both of these sets of priorities by choosing the upgrade that achieves the most economic option without increasing recurrent CO_2 emissions (i.e. upgrades that increase recurrent CO_2 emissions are rejected).

6.1 Heating Systems

This section compares different heating systems: appliances and fuels. Heating requirements for a chosen heating schedule, set point temperature, and heated area will have to be delivered by a specified heating source (fuel) and system (which has a known efficiency). Different heating systems will have different impacts as explained below.

The ***net energy*** required for space heating will depend on the difference between heat losses and other gains, the set point temperature and area to be heated. Obviously the higher the difference between indoor and outdoor temperatures, the more heating power will be required to maintain comfort levels.

The ***purchased energy*** to provide the net energy depends on the efficiency of the heating system and the heating source. For example an enclosed wood burner can convert purchased wood energy into net energy at an efficiency of about 65 - 80%.

The ***primary energy*** required will depend on the efficiency of supply of the purchased energy. Fossil fuels are primary energy sources that are purchased directly. A significant difference between purchased energy and primary energy occurs for electricity, which is purchased as electrical energy, but is generated from the power of burning fuels or falling water. Thermal power plants require nearly three units of primary energy to produce one unit of electrical energy available for purchase. Of course, the burning of primary fossil fuels results in net CO_2 emissions. The current mix of hydro and thermal generation facilities (2006) have an overall emission factor of 0.180 kg CO_2 per kWh. New electricity demand that arises in part from new building or retrofits from a non-electrical source of heat are associated with new generation capacity that must be built. The Ministry for the Environment estimates that the planned mix of new capacity due for completion in 2006-2012 has an overall average emission factor of 0.650 kg CO_2 per kWh. The increase is due to a greater proportion of thermal plant.

Table 13 presents the *cost and CO_2* associated with the delivery of 1 kWh of heat energy, for a selection of heating systems and sources taking into account the efficiency of the heating system. Fuel prices are for Dunedin, unless indicated otherwise. Efficiencies and costs are indicative.

Table 13 Cost and CO2 per kilowatt-hour of Net Heating Energy for Heating System and Fuel

Cost and CO_2 emissions to deliver 1kWh using different heating systems				
Heating Source		Heating System Efficiency	Net Cost 2005/2006	Fuel CO_2
Heating System	Fuel	%	$/ net kWh	$kgCO_2$/net kWh
Heat Pump	Electricity New Supply*	250%	$0.07[3]	0.260[2]
	Electricity Current	250%	$0.07[3]	0.072[5]
Wood Burner	Wood (Dry)	70%	$0.13[4]	0.000[5]
Multi Burner	Coal	65%	$0.08[4]	0.505[5]
Pellet Fire	Pellets	75%	$0.11[1]	0.014[1]
Wood Burner	Wood (Wet)	70%	$0.15[4]	0.000[5]
Electric Heater	Electricity New Supply*	100%	$0.17[3]	0.650[2]
	Electricity	100%	$0.17[3]	0.180[5]
Unflued Gas Heater	LPG	100%	$0.14[4]	0.217[5]
Flued Gas Heater	Natural Gas (North Is)	89%	$0.11[3]	0.211[5]
Open Fire	Coal	15%	$0.35[4]	2.190[5]
	Wood (Dry)	15%	$0.59[4]	0.000[5]
	Wood (Wet)	15%	$0.71[4]	0.000[5]

(1) Chapman, Westergard, Heater Analysis, 2005
(2) Ministry for the Environment, Electricity Emission Factor Review 2004
(3) Ministry for Economic Development, 2007, Energy Data File (2006 prices)
(4) Energy Studies, University of Otago, 2006
(5) Ministry for the Environment, New Zealand's Greenhouse Gas Inventory 1990–2005, Annex 2
Heating System Efficiencies and Fuel costs are indicative. Heat pump efficiency change with outside temperature. Open fires may have efficiencies from 15-35%. Wood burners and pellet fires vary from 65-88%.
*New Supply uses the carbon emission factors established in a 2004 MfE Report for the expected mix of 1.45 GW of generation capacity to be added 2004-2012 (2).

The cost of the space heating energy and the resulting CO_2 emissions are calculated from the annual net heating energy obtained from ALF3, and the cost and CO_2 factors presented above.

Table 14 presents the recurrent cost and CO_2 emissions to deliver 1,000 kWh net energy using different heating systems. The data does not include CO_2 emissions from the capital items or the costs associated with the capital purchase.

Table 14. Recurrent costs and CO_2 emissions for Fuel and Heating System to deliver 1000 kWh of Heating Energy

Recurrent costs and recurrent CO_2 emissions to deliver 1,000kWh			
Heating Source		Total Cost (2005/06)	Total CO_2
Heating System	Fuel Purchase	$	Kg
Heat Pump	400 kWh of Electricity - New Supply*	$69	260
	400 kWh of Electricity	$69	72
Wood Burner	2.5 m^3 of Wood (Wet)	$152	0
	1.8 m^3 of Wood (Dry)	$136	0
Multi Burner	9.4 20kg bags of Coal	$80	505
Pellet Fire	13.3 20kg bags of Pellets	$113	14
Electric Heater	1000 kWh of Electricity - New Supply*	$173	650
	1000 kWh of Electricity	$173	180
Unflued Gas Heater	8.8 9kg bottles of LPG	$142	217
Flued Gas Heater	1124 kWh Natural Gas (North Island)	$114	244
Open Fire	40.7 20kg bags of Coal	$346	2,189
	8.5 m^3 of Wood (Dry)	$635	0
	2.7 m^3 of Wood (Wet)	$711	0

*New Supply refers to additional generation capacity 1.47 GW planned 2004-2012, and the associated carbon emissions
^The above data does not include CO_2 emissions from the capital items or the costs associated with the capital purchase

Wood prices are subject to considerable variation as wood can be scavenged in some areas for only the cost of the collection time and transport. The price used in the table is for commercially supplied wood, which represents the upper end of prices. The following fig. 46 shows a graphical comparison between the systems presented in Table 14. A heat pump provides the least expensive heat, assuming the commercial supply of wood. A wood burner provides the least expensive heat that has no carbon emissions. However only modern burners fuelled with dry wood will have low particulate emissions. As expected, open fires are the most expensive systems to run with the highest CO_2 emissions if used with coal.

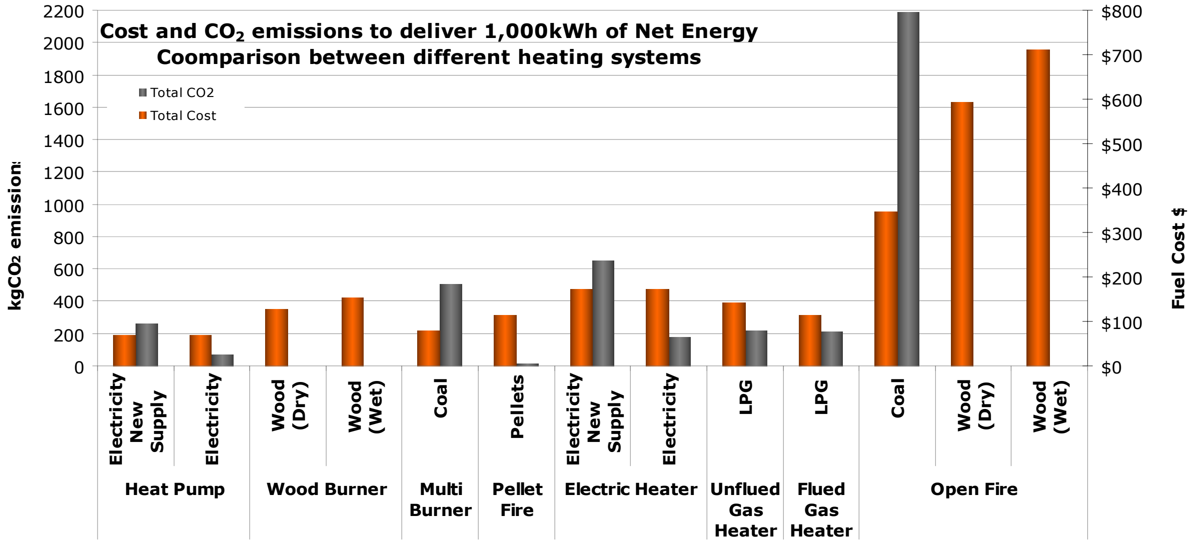


Figure 46. Cost and CO_2 for various energy sources and heating systems to deliver 1,000kWh of net energy.

In addition, if the same money is spent on fuel using different heating systems, thermal comfort will vary widely. The following table 15 shows the heat output for $1,000 (2005-2006 dollars) of purchased energy for different heating systems for our state house as upgraded to H1-1 (HNZC upgrade package). As can be seen Open fires are the most expensive followed by electric heaters achieving very low indoor thermal comfort when comparing with other systems.

Table15. Net Energy, CO_2 and thermal comfort achieved for various heating systems for $1,000 cost.

Heating Systems		**Energy and CO_2**		**Thermal Comfort: Heating Schedule achieved**											
		Net Heat	**Net CO_2**	EVE16	EVE18	ME16	EVE20	ALL16	ME18	ME20	ALL18	24H16	ALL20	24H18	24H20
Option	**Fuel**	**NET kWh**	**$kgCO_2$**												
Electric Heater (EH)	Electricity	5,784	342												
	Electricity ND*	5,784	3,759												
Heat Pump (HP)	Electricity	14,459	342												
	Electricity ND*	14,459	3,759												
Multi Burner	Coal	10,201	5,153												
	Wood (Dry)	6,825	-												
	Wood (Wet)	6,094	-												
Open Fire	Coal	2,354	5,153												
	Wood (Dry)	1,575	-	none											
	Wood (Wet)	1,406	-	none											
Pellet Fire	Pellets	8,824	120												
Unflued Gas Heater	LPG	7,099	1,544												
Flued Gas Heater	LPG	6,318	1,544												
Wood Burner	Wood (Dry)	7,350	-												
	Wood (Wet)	6,563	-												
Wood Burner +EH**	Wood/Electricity	6,452	190												
Wood Burner +HP**	Wood/HP	9,524	114												

EVExx = Evening Heating to xx ºC
Mexx = Morning and Evening Heating to xx ºC
ALLxx = All Day Heating from to xx ºC
24xx = 24 Hours Heating to xx ºC
* Electricity New Supply
** Assumes 50% of net energy delivered by Wood Burner and 50% delivered by either Electric Heater (EH) or Heat Pump (HP).

6.2 Upgrade options for House 1

House 1 is thought to be a typical state house in Dunedin and is used when modelling various upgrade options.

First, we investigated changes in net annual energy requirements for a house with various retrofit options. Secondly, we show how the installation of various heating systems will affect the annual fuel financial cost and recurrent CO_2 production. Finally, we look at lifetime cost and CO_2 reductions.

The initial upgrade financial costs are calculated from the materials and labour for each upgrade and are presented in table 16. In addition the CO_2 contributions (for reference only) for each upgrade are also presented in the table. Data for embodied energy and CO_2 emissions was found some (but not all) materials, this values do not include extra emissions associated with transportation, decommissioning, etc.

Table 16. Capital costs and Carbon Emissions(embodied energy) for Potential Upgrades Materials

Upgrades		**Materials**	**Cost**	**CO_2**
		Description	**$**	**Kg**
Base Case		No insulation	$0	0
CEILING	Insulfluf	Macerated Paper0.1	$616	42
	Insulfluf & Polyester	Macerated Paper0.1	$616	42
		Polyester0.15	$1,238	627
	Polyester	Polyester0.15	$1,238	627
FLOOR	Expanded Polystyrene Sheers	Polystyrene (EPS)0.05	$1,986	623
	Foil	Aluminium foil - Sheet under joist 0.001	$649	243
HEATING SYSTEM	Flued Gas	Yunca Jervois 6.4kW	$3,320	unknown
	Heat Pump	Fujitsu 8.5kW	$3,199	unknown
	Multi Burner	Masport Piccolo	$3,529	unknown
	Pelletfire	Nature's Flame Classic	$4,034	unknown
	Wood Burner	Masport Piccolo	$3,529	unknown
WALLS	Formaliner	Fiberglass0.7	$177	28
		Gypsum0.01	$2,066	306
		Partial Demolition*	$1,520	0
		Polystyrene (EPS)0.06	$1,579	215
	Fibreglass and regib	Fibreglass 0.7	$841	1,024
		Gypsum 0.01	$2,066	281
		Partial Demolition*	$1,520	0
WINDOWS	Double Glaze	Aluminium windows double glazed	$10,925	6,104
	Drapes	Fabric0.005	$3,960	13
* This includes the costs of removing the original GIB board and associated components				

6.2.1 Comparison of Upgrades to reduce heat losses

Table 17 presents a comparison of possible upgrades applied to the original house. As can be seen, investing in each one of the upgrade options will reduce annual energy requirements by different amount

Table 17. Upgrade capital cost and annual heating requirement for various upgrades options.

House Configuration		**Upgrade Capital Cost**	**Annual Heating Energy for ME18 Schedule**	
			kWh	% reduction
H1-A	HOUSE 1 as built (1960s)	$0	11,481	0%
Option 1	Add Window Drapes	$3,960	10,998	4%
Option 2	Add Double Glaze Windows	$10,925	10,740	6%
Option 3	Add Underfloor Foil Insulation	$649	10,317	10%
Option 4	Add Underfloor EPS Insulation	$1,986	9,909	14%
Option 5	Add Ceiling Insulfluf	$616	8,784	23%
Option 6	Add Ceiling Polyester	$1,238	8,298	28%
Option 7	Add Ceiling Insulfluf & Polyester	$1,854	8,130	29%
Option 8	Add Wall Insulation (Fibreglass and ReGib)	$4,427	9,892	14%

For example, House 1 as built in the 1960's would have required 11,400 kWh of space heating energy to heat completely in the morning and evening to 18°C (ME18 heating schedule).

Fig. 47 helps to visualize the options available. Each option will have an initial cost and a reduction in heating achieved. The steepest paths are the retrofit options that give the largest reduction in net heating energy required for the least capital cost. Note that the energy requirements are for possible upgrades done to the original house (i.e. the upgrades are not cumulative).

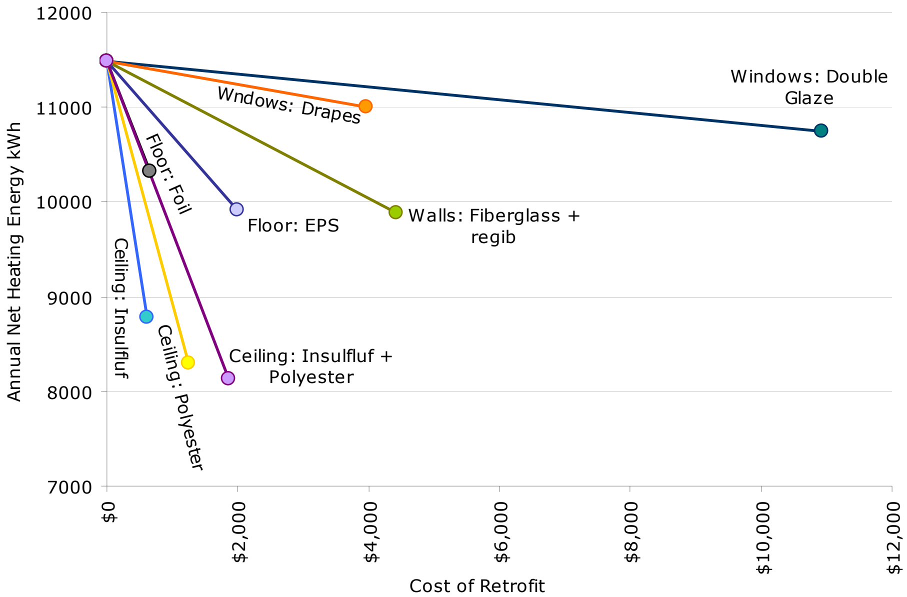


Figure 47. Annual net heating requirements for various retrofit options with ME 18C from House 1 as originally built.

As it can be seen, the initial installation of Insulfluf in the ceiling was the most cost effective choice as it achieved the greatest drop in annual heating energy for the lowest capital cost. Polyester alone would have given a greater reduction, but for slightly higher cost. The impact of both ceiling upgrades (insulfluf and polyester) installed provided the greatest reduction, but for a higher capital cost.

Underfloor foil is also shown as a good choice. Expanded polystyrene sheets underfloor insulation reduces annual heating energy by a small amount in addition, and could have been chosen instead.

After these first steps, the next most cost effective heat loss reduction retrofit is the installation of insulation in the walls. This is a more cost effective step than installing double glazing or adding quality drapes on the windows, unless lower costs are achievable for either installation.

6.2.2 Comparison of Heating System Upgrades

A heating system upgrade will have no effect on the annual net heating requirements of a house, but will change the purchased energy and the CO_2 emission produced. Using different systems will have different costs and different recurrent CO_2 emissions.

This section presents the effect of choosing different heating systems to meet the net energy requirements for each upgrade option presented in the previous section (fig. 47). Energy requirements for each upgrade option are shown on the right side of both figures. First, fig. 48 presents the cost to deliver the net energy required using different heating system. Secondly, fig. 49 presents the recurrent CO_2 emissions for each of the options and should be viewed together with the first fig. to asses the overall impact of choosing a heating system.

For example, after applying the ceiling upgrade consisting of polyester blankets, about 8,000 kWh of annual net heating energy is required. This heating energy can be obtained using coal burned in a multi-burner for about $200 per year or with more than $1,200 worth of wood used in an open fire. Both options will meet the energy requirements but will have very different levels of recurrent CO_2 emissions.

By reading both charts together with the heating requirements for each upgrade option, we can examine upgrade costs, annual heating requirements, annual fuel costs and recurrent CO_2 emissions for various heating system retrofits.

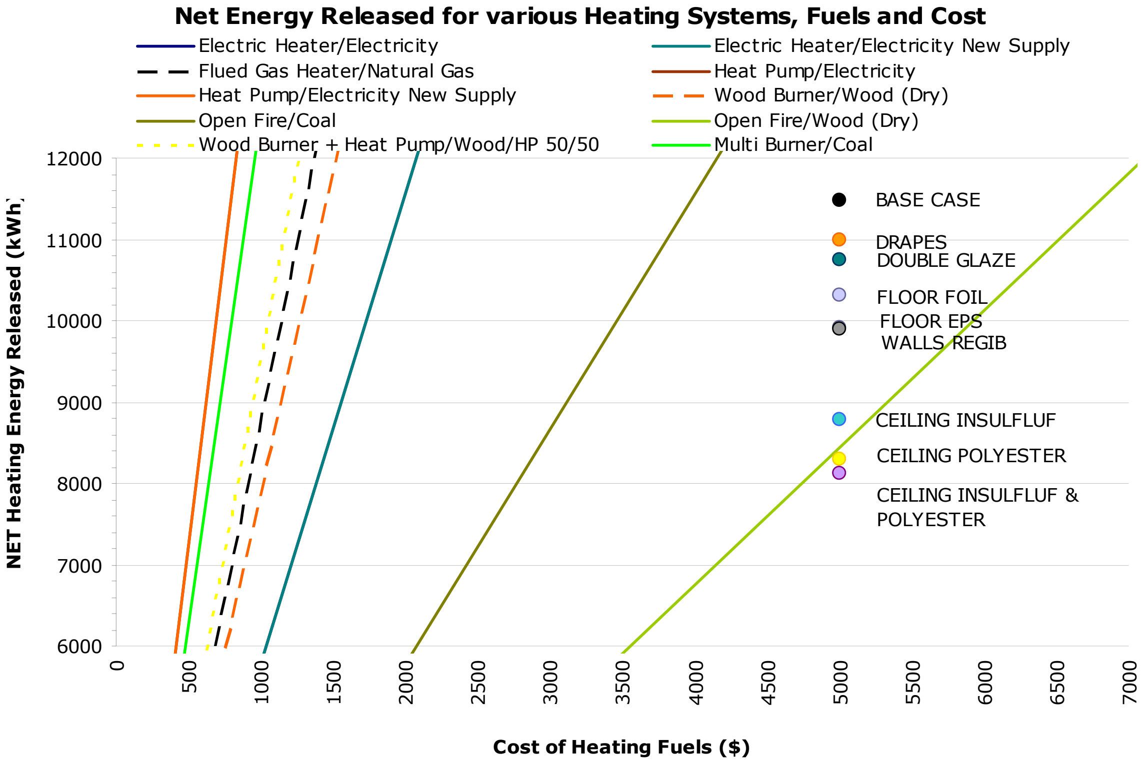


Figure 48. Net Energy released for various heating systems, fuel and costs

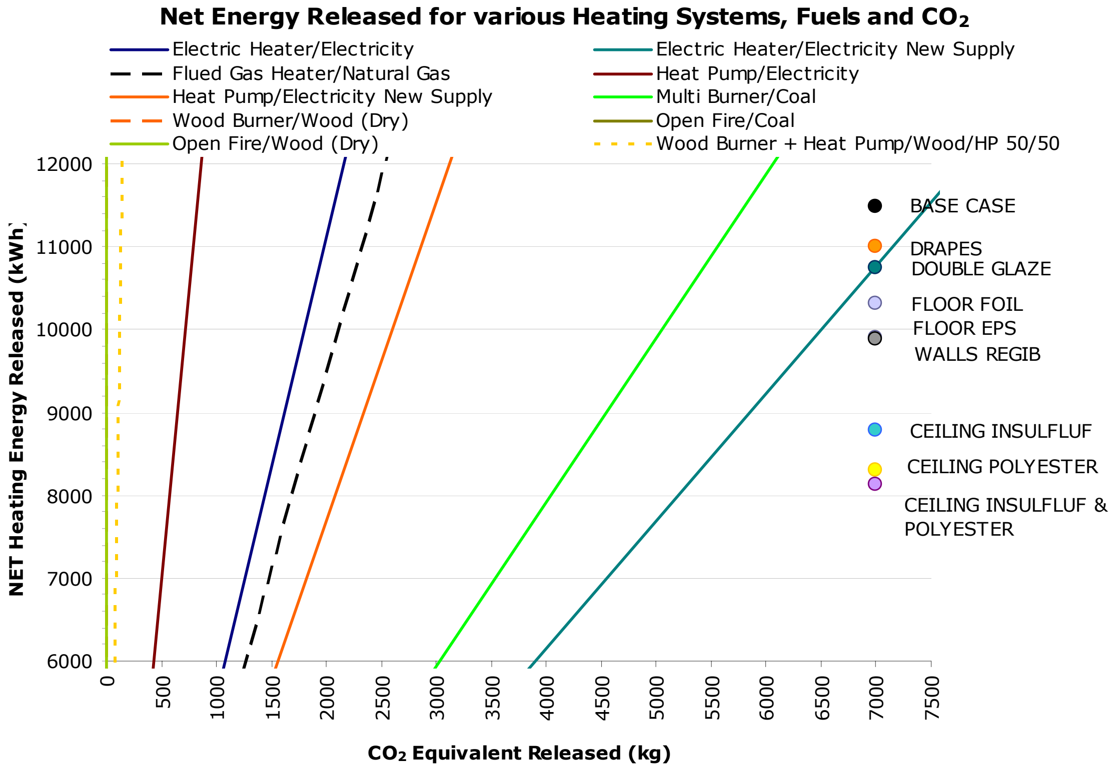


Figure 49. Net Energy released for various heating systems, fuels and CO_2.

6.2.3 Suggested Upgrade path

The historical upgrades undertaken on the HNZC houses were identified and modelled in 3 steps: H1-A was the original non-insulated house, during H1-B insulfluf was installed on top of the ceiling and H1-C provided extra polyester on top of the ceiling. H1-1 calculated the addition of underfloor insulation and presents the current HNZC upgrade package. These only take into account upgrades done to the building fabric.

Further improvements are shown in the following fig. 50. As can be seen insulating the walls or improving air-tightness are the next most effective heat loss reduction strategies which gives higher reduction in annual heat requirements for the lowest cost of investment.

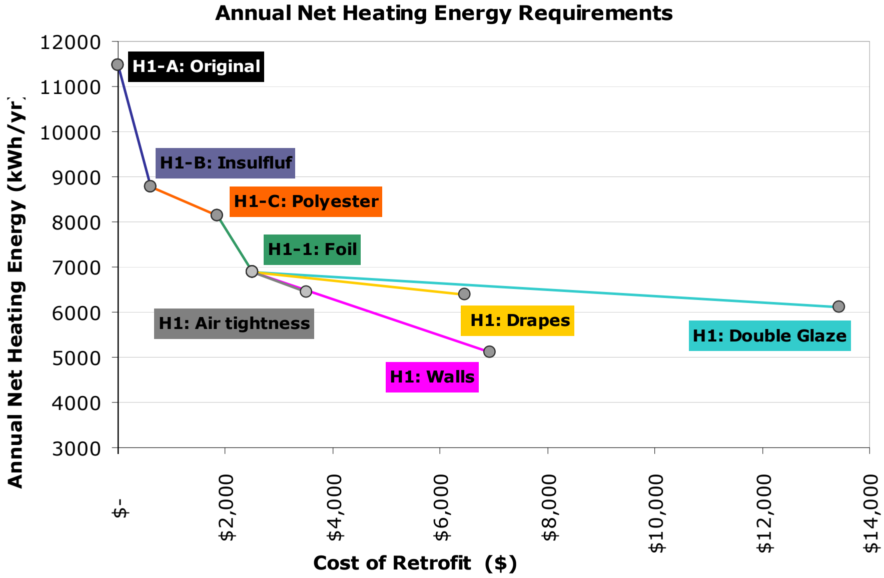


Figure 50. Annual Net heating requirement vs. cost of various retrofit options.

In addition, in some houses, upgrades of heating system also occurred, this step was named H1-BB and involves the replacement of open fires for wood burners. It was considered to be done after the insulfluf ceiling upgrade and before the more recent HNZC full upgrade package.

Ranking the options

Once we understand the impact of each upgrade option (reducing heat losses) and the differences between choosing a heating system, we proceeded to integrate them into a single upgrade path.

To do this, different upgrade options were ranked to identify the best option. This was done by calculating the ratio of annual energy costs to capital costs. Historical upgrades have also been incorporated to the table in order to visualize how they compare with other available options.

Table 18. Ranking of upgrade options

Ranking Options by COST $ *		Step 1 H1-A	Step 2 H1-B	Step 3 H1-BB	Step 4 H1-C	Step 5 H1-D	Step 6 H1-E	Step 7 H1-F	Step 8 H1-G
AIRTIGHNESS		1.12	1.16	0.52	0.53	0.54	**0.37**	choose	
CEILING	Insulfluf	**11.71**	choose						
	Insulfluf & Polyester	4.83	rej						
	Polyester	6.88	1.41	**0.63**	choose				
FLOOR	EPS	2.12	2.21	0.99	1.00	rej			
	Foil	4.80	5.00	2.24	**2.27**	choose			
HEATING SYSTEM	Flued Gas	4.99	3.82	-0.09	-0.08	-0.07	-0.87	-0.82	-0.60
	Heat Pump	7.68	5.87	1.82	1.68	1.43	0.60	0.56	0.41
	Multi fuel Burner	6.69	5.12	1.44	1.34	1.13	0.38	0.35	0.26
	Pelletfire	5.12	3.92	0.70	0.65	0.55	-0.11	-0.10	-0.08
	Wood burner + Electric	5.51	**3.68**	choose					
	Wood burner + Heat Pump	n/a	n/a	1.06	0.98	**0.83**	choose		
WALLS	Formaliner	0.82	0.86	0.38	0.39	0.40	0.27	0.27	rej
	Fiberglass + Regib	0.96	1.00	0.45	0.45	0.47	0.32	**0.32**	choose
WINDOWS	Double Glaze	0.18	0.19	0.08	0.09	0.09	0.06	0.06	**0.06**
	Drapes	0.33	0.34	0.15	0.15	0.16	0.11	0.11	0.11
Heating Kg CO_2 reduction from base to chosen option*		**23%**	**99%**	**7%**	**15%**	**59%**	**7%**	**27%**	**12%**

* For details on calculations of each option see Appendix C.
** Wood burner + Electric Heater or Heat pump assumes 50% net energy delivered by each system.

The upgrades are ranked as given in the above table 18. They do not account for any rebound effect (i.e. increase in indoor temperatures) and they assume a constant ME18 heating schedule.

Any changes in heating energy due to the upgrades will deliver the energy needed to meet this heating schedule, thus 100% energy saving will occur.

The original un-insulated house (H1-A) was modelled as having an open fire and heated by coal only. As can be seen, the first thing done in the house: insulating the ceiling and replacing the open fire with a wood burner are ranked as the best options. In order to provide a more realistic situation, heating assumptions needed to be made, we then assumed that even after the wood burner was installed (H1-BB); the house was heated by a combination of wood burner and electric heater (50% of the net energy required was provided with each system). At this stage choosing to install any type of floor insulation or a heat pump would be ranked higher than installing extra ceiling insulation.

The HNZC standard upgrade package has been chosen instead, assuming the house is heated with a wood burner and electric heater. At this stage it can be seen that the best ranked options are: installing a heat pump, insulating the walls and improving air-tightness. Details on the calculations showing these rankings can be found in Appendix C.

The following figures 51 and 52 show the optimum upgrade path for both 'recurrent cost' and for 'recurrent CO_2 emissions' as identified in the previous table. After the full upgrade path (H1-A to H1-G), if same indoor conditions are achieved, a reduction of 59% of net energy required is achieved which is translated into 90% reduction of heating costs. As can be seen, the horizontal lines represent the change in heating system, which do not change the net energy required but have an effect in both: cost and operational CO_2 emissions.

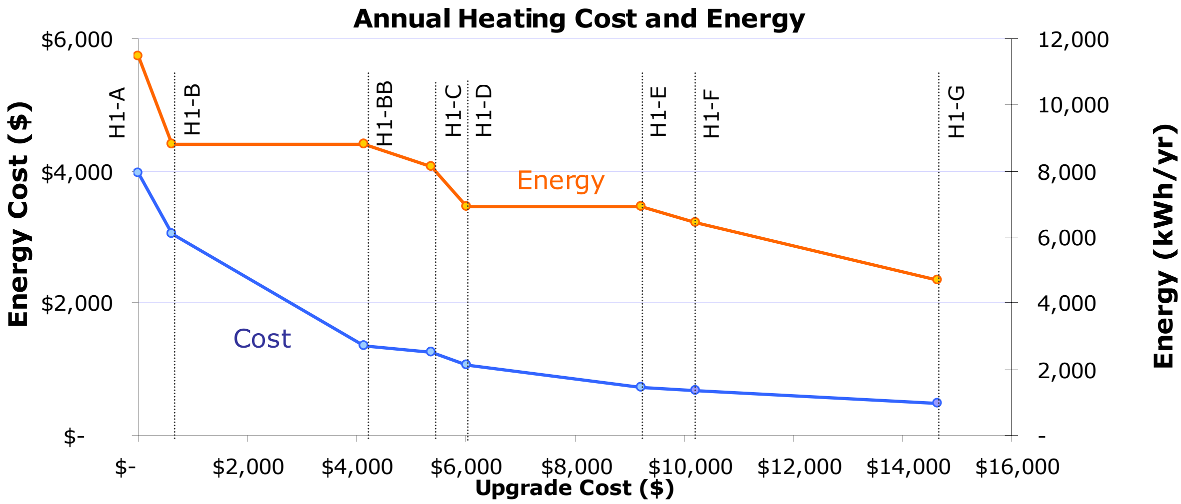


Figure 51. Annual Net Energy requirements and Costs for a path of historical and optimal upgrade stages.

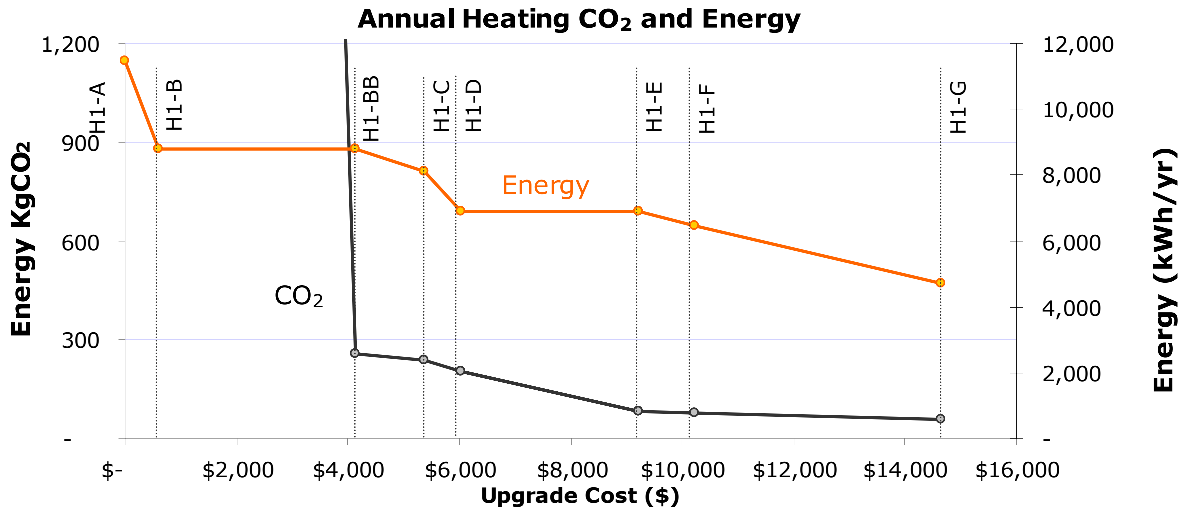


Figure 52. Annual Net Energy requirements and recurrent CO_2 emissions for a path of historical and optimal upgrade stages.

References for fig 47 & 48: H1-A: Base Case; H1-B: Add insulfluf; H1-BB: Add Wood burner; H1-C: Add ceiling polyester; H1-D: Add underfloor foil; H1-E: Add airtightness; H1-F: Add wall insulation.

Reducing heat loss by adding insulation will help householders save money on heating costs or allow them to improve indoor comfort by reducing the annual heating energy requirements. Heating system and fuels have the largest impact on cost and CO_2 emissions associated with domestic heating.

Costing the upgrades over time

A 10 year life time is presented to view the effects of various upgrades options in the near future. This kind of analysis makes sense when it can be assumed that all efficiency increases and cost reductions result in monetary savings. As mentioned before a rebound effect could affect the amount of monetary savings.

This analysis is to be considered as a reference only, a long term life cycle analysis (i.e. 50 -100 years) could be done which should take into consideration other costs related to maintenance or replacement of upgrades (i.e. replacing a heating systems) to asses the full environmental impact of undertaken upgrade options. As mentioned before these are not considered in this analysis and thus only a 10 years period is presented. After 10 years some of the systems will need to be replaced (i.e. heat pumps).

Discounting capital costs causes savings far in the future to be worth less than savings today. This is illustrated in the curves shown in fig. 53. The current cost of heating is represented by the black line (non upgraded house, H1-A). The lifetime costs of various possible upgrades are shown, assuming that all savings are not spent on more heating. The curves start at a higher position on the chart on the left because upgrades cost money, but rise more slowly, because the upgrades result in lower fuels costs. The year at which two lines cross is when the upgrades are economically neutral based on fuel cost savings. This analysis only looks at these direct economic effects. Other benefits of upgrades are not considered. It is assumed that all upgrades last for the entire period below. All upgrades except for the Double Glazing become economic after.

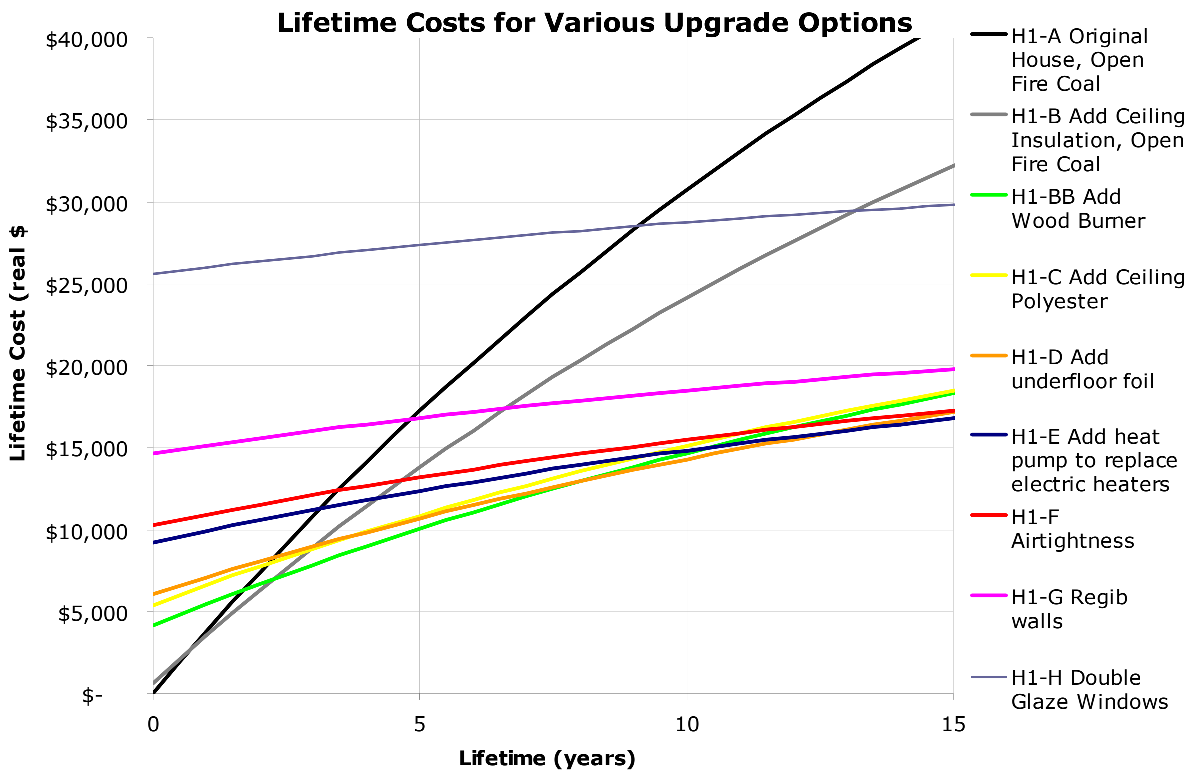


Figure 53. Initial and Discounted Recurrent Financial Costs from 1 to 15 years.

Summary

Adding insulation will increase the efficiency of heating a house, helping occupants save on fuel costs, or allowing them to heat to a higher temperature or longer, for the same fuel costs. When energy comes from fossil fuels, carbon emissions, need to be taken into account.

This chapter has seen the inclusion of heating system upgrades to the analysis. The choice of heating system has a large effect on the financial and carbon costs of household heating. Wood burners, multi burners, heat pumps, gas fires, and pellet burners all release a large fraction of the primary energy fuel to usefully heat the house.

It is obvious that insulation and heating system upgrades will improve comfort. An economically sound sequence of upgrades will first see the insulation of the ceiling, then the floor, then the installation of an efficient heating system, and then draught proofing and adding of wall insulation. For houses with similar glazing areas to our case study, only thereafter is double glazing an economic choice although there may be some cost saving in doing the wall insulation and the double glazing together as both disturb the interior cladding.

It is known that state houses in NZ are under heated, and we believe that gains in efficiency, either from increased insulation or improved heating systems, will result in more comfort for the same cost of fuel rather than decreased consumption. A change in heating system placement or open plan designs which promote an enlargement of the heated area of the house can, however, increase heating demand.

To achieve a reduction in carbon emissions from household heating in these situations we must support the use of less carbon intensive fuels, and consider what sort of household heating practices are supported. Electrically driven heat pumps clearly provide more comfort for the same cost and fuel use than electrical heaters. However, the new generation capacity that is planned to support increased electricity use has a carbon intensity such that the operation of the heat pump will result in a similar level of carbon emissions to burning coal in a multi-burner.

Wood is a good choice of fuel. Its price is low and variable, and it produces no net carbon emissions. With wood as a fuel, warm homes and a lower carbon footprint are both possible.

Thus the final upgrade path chooses wood as a heating fuel, and recommends that upgrades do not preclude the ability to heat a small area.

CHAPTER 7 : Conclusions and Recommendations

Our last report showed that the energy efficiency upgrade program undertaken by HNZC worked in the sense that it improved the indoor temperature by 0.6 degrees (annual average increase) and reduced the space heating energy consumption (between 5% and 9% reduction) but it also failed in the sense that it has not provided indoor temperatures commensurate with healthy living, as defined by the WHO, in the cooler parts of the country. This finding is not entirely surprising because if the upgrade, which consisted of installing insulation in the ceiling and under floor, was sufficient to produce an energy efficient house with a healthy indoor environment in NZ then the current regulations demanding floor, ceiling and wall insulation and the mooted regulations demanding in addition double glazing in the cooler parts for the country would be superfluous.

There is no doubt that in the long term fossil fuel energy sources will not be available and that the cost of providing alternative space heating will be higher than present space heating costs. There is thus a good incentive to future proof housing in NZ while we do have access to relatively cheap energy sources. In addition there is now considerable pressure in terms of reducing green house gas emissions. It is easy to improve indoor temperatures with inexpensive fossil fuels. Our challenge is to achieve comfort with low fossil energy use.

However, even with the sorts of mitigation envisaged by the Kyoto Protocol, anthropogenic global warming is expected to increase the earth's average ambient temperature by a minimum of 2^oC and up to possibly 6^oC by the end of this century. This range of temperature increases will not be uniform across the globe and will place considerable uncertainly on how NZ should plan for its future housing. More research needs to be done in this area, looking at the impact of climate change in the future of NZ housing.

Going the next step

The original HNZC upgrade was simple to implement and reasonably cheap to fund, going the next step will be more difficult and more expensive. Each upgrade step will lead to significant monetary costs but can lead to reductions in gas emissions and reduction in energy consumption, or an increase in thermal comfort. Funding the costs will be a challenge but a challenge that will have a payoff over the long term.

After the original HNZC's upgrade package more than 70% of the remaining heat losses were found to occur through the walls and windows.

The second stage of our study has shown that improving the whole house building fabric by retrofitting floor, wall insulation and double glazing to a state house would increase the calculated thermal resistance R value of the building envelope from 0.40 m^2K/W for the original house to 0.64 m^2K/W (measured 0.67 m^2K/W) for the HNZC upgraded house to a calculated value of 1.11 m^2K/W (measured 0.99 m^2K/W) for the fully insulated house. This is an improvement in the calculated value by a factor of 2.8 for the whole upgrade history.

The upgrade undertaken for the living area of House 2 improved the room R value from an original calculated R value of 0.41 m^2K/W to a calculated R value 0.48 m^2K/W after the 70s retrofit (measured 0.47 m^2K/W) to a final calculated R value of 0.91 m^2K/W for the upgraded living area in House 2 (measured 1.09 m^2K/W). This is an improvement in the calculated value by a factor of 2.2 for the whole upgrade process.

Monitored improvements were, however, somewhat lower than expected. This was thought to be due to uncertainties in thermal bridging, changes in air infiltration, lower than expected R values due to gaps between the structure and the insulation, higher infiltration rates than expected, etc. It is anticipated that further improvements, thicker insulation, quality control during the upgrade process and substantial decrease in air infiltration could easily give an overall R value of 1.2 m^2K/W for the whole house. This value should be compared to the value obtained by modelling House 1 (H1-6) to the current (1996) minimum building code requirements for zone 3 which gives an overall R value of only 0.79 m^2K/W. Our tested upgrade results in a house that has an R value 5% higher than the current code (see chapter 4).

These substantial improvements came at a cost of around 120$/m^2 of building envelope. With a large scale roll out economies of scale will occur and it is estimated that considerable reductions could easily be achieved.

Monitored improvements differed from those calculated. The differences were less than 20%. The difference between the calculated values for R and the experimental values is in agreement with other experimental studies [96][36].

Space heating requirements and indoor temperatures

Even with the improved building fabric, healthy indoor temperatures compatible with WHO recommendations are not likely to be achieved in retrofitted state housed due to their lack of space heating. Thus the houses will still need space heating.

The annual heating demand for a house depends not only on the thermal properties of the house but significantly on the heating schedule chosen and the size of the heated area. Our earlier work suggested that occupants generally did not heat whole houses in NZ and generally only heated for a small part of the day (evening) during the winter months. Our data showed that occupants of housing in Dunedin could be exposed to indoor temperatures of less than 12°C, for nearly half (48%) of a 24 hour day during winter months. Also, minimum temperatures (averaged over the sample) recorded in the winter months were between 5°C and 5.4°C. The earlier work also showed that due to the time lag in heating a house, some of the gains from improving the building fabric were only realised after 12 midnight, especially when evening heating cycles were used. UK regulations to reduce fuel poverty consider 24 hour heating (or large fractions of a 24 hour period depending on the house occupancy [37] to be the norm when deciding on the level of heating needed to give an adequate healthy indoor environment. Although these recommendations may be considered excessive by NZ practice at the present time the situation in the UK 20 years ago would been similar.

In terms of energy requirement for space heating we can conclude that similar energy is required to heat the whole house for the evening schedule only for 18°C before the upgrade, as is needed to heat the same house for the whole day to 16°C after the upgrade as can be seen in fig. 54.

The figure is also showing energy requirements for heating the house to a potential higher insulation levels. Without modifying the structure (e.g. increasing north face opening to achieve higher solar passive heating, modifying levels of thermal mass, etc.), this would be the minimum realistic level that could be achieved in terms of heating requirements.

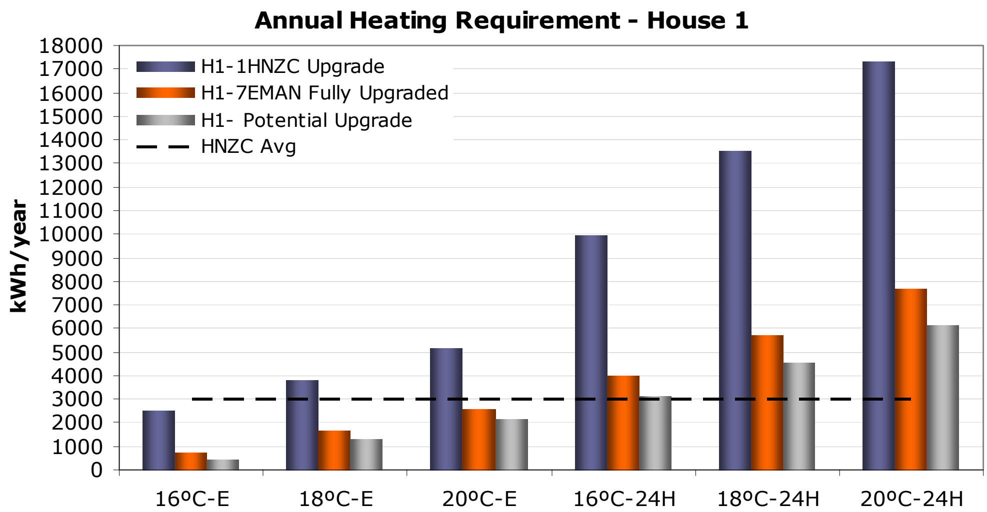


Figure 54. Annual heating requirement for various upgrade stages.

Choosing the right heating system

The energy required to be purchased to deliver a certain kWh of *net* heating energy to the indoor environment will vary depending on fuel and the efficiency of the heating appliance.

The following graph shows the comparison between the systems in terms of Cost and CO_2 emissions to deliver 1,000kWh of energy (see fig. 55). Prices and efficiencies are indicative. Commercial wood and coal prices are used in this chart, but the fuels can in many cases be obtained for much less. Costs are for Dunedin, in 2005 and 2006 dollars.

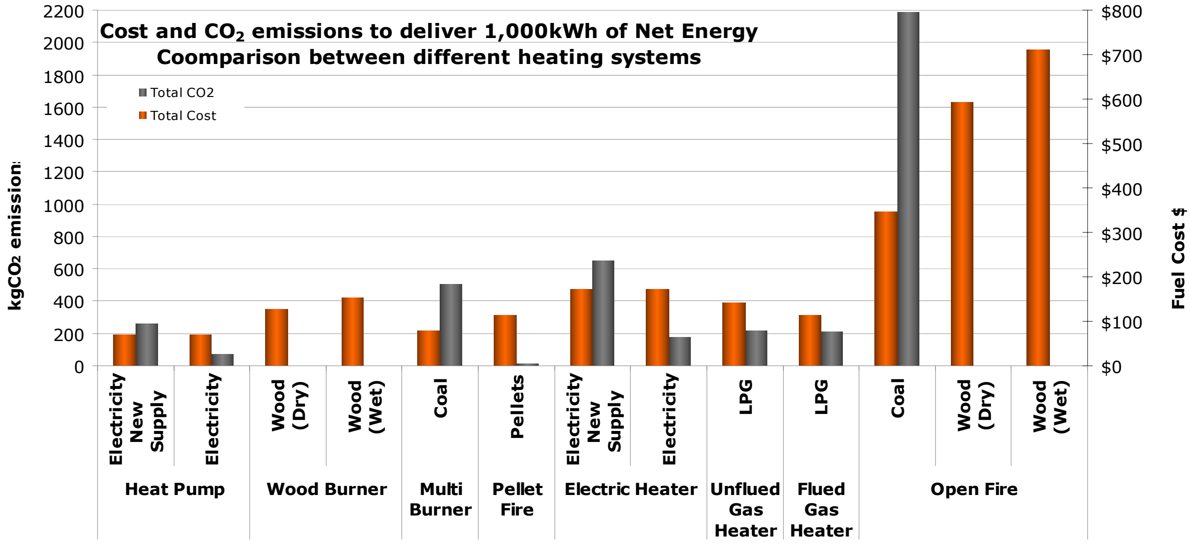


Figure 55. Cost and CO_2 for various energy sources and heating systems to deliver 1,000kWh of net energy.

Upgrade Path

Our analysis has concluded that historical HNZC retrofits of ceiling insulation, multi-burner inserts, and floor insulation have been appropriate, but that additional retrofits are needed to give adequate housing in the colder regions of New Zealand

After our analysis of heat loss reduction and heating system upgrades the following priorities were identified:

1) Insulate the ceiling (Completed by HNZC)
2) Insulate the floor (Completed by HNZC)
3) Install a low emissions wood burner or pellet fire (if not done yet)
4) Install a heat pump that will replace electric heaters used elsewhere in the house.
5) Improve airtightness
6) Insulate walls
7) Install double glazing (or drapes)

It must be noted that we did not investigate the benefits of improving and capturing solar gains with conservatories and the like. This area requires further modelling to quantify the benefits.

Recommendations

Our recommendations, in view of mitigating CO_2 emissions and coping with future energy supply constraints, is that there is some urgency in future proofing NZ houses and that a start should be made on public housing. Our earlier work showed that the standard HNZC upgrade has not produced an improvement in indoor temperatures that would be considered commensurate with healthy living, for areas of the southern South Island. Based on an understanding of net temperature differences and existing ambient temperatures, it is likely that such conditions exist for most of the remainder of the South Island and for the cooler parts of the North Island.

Some areas need attention, these being:

- Going the next step in terms of building fabric upgrade, including wall insulation and in the longer term double glazing. The improvement to the thermal properties should be sufficient to bring the housing stock up to that required by the current building code or better.
- Providing a path for efficient space heating at a cost commensurate with the circumstances and the income of the occupants of state housing. Heat pumps are suggested as a particularly efficient source of space heating only when they replace the use of other electrically driven heating.
- Replace lower efficiency wood burners with newer, cleaner wood burners or pellet fires. Replacing solid fuel burners with heat pumps is not recommended, as this new electricity demand will lead to electrical capacity problems and higher carbon emissions for New Zealand.

- Support the efficient practice of zoned heating. In some houses insulating one room completely may be appropriate. Allow for comfortable temperatures in the living room(s), and at least the maintenance of minimum temperatures in the rest of the house, possibly via a combination of solid fuel heating in the lounge and heat pump heating of the hall and bedrooms.
- Information to tenants on achieving energy efficient healthy housing. Information packs should be provided to all HNZC tenants on how to manage the indoor environment and provide the health and comfort for all age groups. Such packs should also include information of carbon emissions and the value of using energy efficient appliances, curtains and space heating. Advice on managing water vapour sources and the need to isolate the part of the house used to dry clothes should be provided.
- Further analysis to quantify the benefits of zoned heating and passive solar retrofits, including conservatories, is required. There is still much potential for well designed conservatories to reduce heating loads for adjacent rooms.

In addition we strongly recommend that all open fires should be replaced in existing state houses as soon as possible as they are the least efficient systems available for space heating; where possible open fire places should be replaced with enclosed wood burners which comply with the appropriate air quality regulations. The use of coal is not recommended for space heating because of the high levels of CO_2 emissions incurred. One possibility suggested is that a carbon tax be placed on coal so that it is not the cheapest option for heating. Easier ways to access to wood should be encouraged.

A building can be considered as a dynamic thermal system with different thermal inputs and losses:

- solar gains (Q_{Sol})
- ventilation gains or losses (Q_v)
- evaporative heat losses (Q_{xx})
- internal heat gains and (Q_{xxx})
- conduction heat gain or losses (Qc)

Thermal equilibrium exists when the sum of all heat flow terms is zero:

$$Q_v + Q_C + Q_C + Q_C + Q_C = Q_T$$

If the gains are greater than zero ($Q_T > 0$), the temperature inside the building will increase and if the losses predominate the building will cool down ($Q_T < 0$).

For the purpose of our investigation, we avoided solar and internal gains by undertaking the monitoring in unoccupied houses during night time. Evaporative heat losses was avoided by drying the building for several days before tests begun, but it is still possible that some evaporative heat transfer could be happening inside the wall, which we could not detect.

Thus, the parameters involved in our heat flow analysis are reduced to conduction and ventilation gains/losses.

$$Q_T = Q_v + Q_C$$

Heat transfer rate ventilation:

Q_v, to estimate air infiltration, we have calculated ventilation heat losses at each stage by undertaking a blower door test. Blower door measurements record the air changes induced in a building by maintaining a small, 50 Pa pressure change. Correlations developed by (Bassett 2001) are used to estimate average air changes (ACH) from forced air changes (ACH50), and thus to calculate Q_v.. The heat transfer rate by ventilation only is then calculated by:

$$Q_v = 0.33 \text{ ACH Volume}$$

Where ACH is the measured air changes per hour and 0.33 accounts for the volumetric heat capacity of moist air (1200J/m³K) and ACH expressed in seconds (1 hour = 3600 s). A blower door was used before and after each upgrade to estimate the amount of ambient air ingress.

In addition wind speed and wind direction was measures at the site to correct ACH. Solar radiation and Relative Humidity was also collected.

Heat transfer rate by conduction:

Qc, is defined by the total conductance of the building fabric (U_E) multiplied by the total area exposed to the exterior and by the difference in temperature between the inside and the outside.

$$Qc = U_E \; A_E \; \Delta T$$

The total conductance U_E of the building fabric is a measure of the conduction ability of all materials, taking into account their thickness; it is calculated using the following formula:

$$U_E = \sum_i U_i \, A_i / A_E$$

Where U_i is defined by the conductivity of materials divided by the thickness (W/m²K), which is the inverse of the R value (m²K/W).

A_i is the area of each element of the building fabric

A_E is the total envelope area.

The heat transfer rate by conduction only (excluding infiltration) is finally represented by the following formula:

$$Q_C = U_E A_E \Delta T \quad \text{or, equivalently,} \quad Q_C = \frac{A_E \Delta T}{R_L}$$

Where $R_L = 1/U_E$ and ΔT is the temperature difference.

Thus: if $Q_T = Q_v + Q_C$, then:

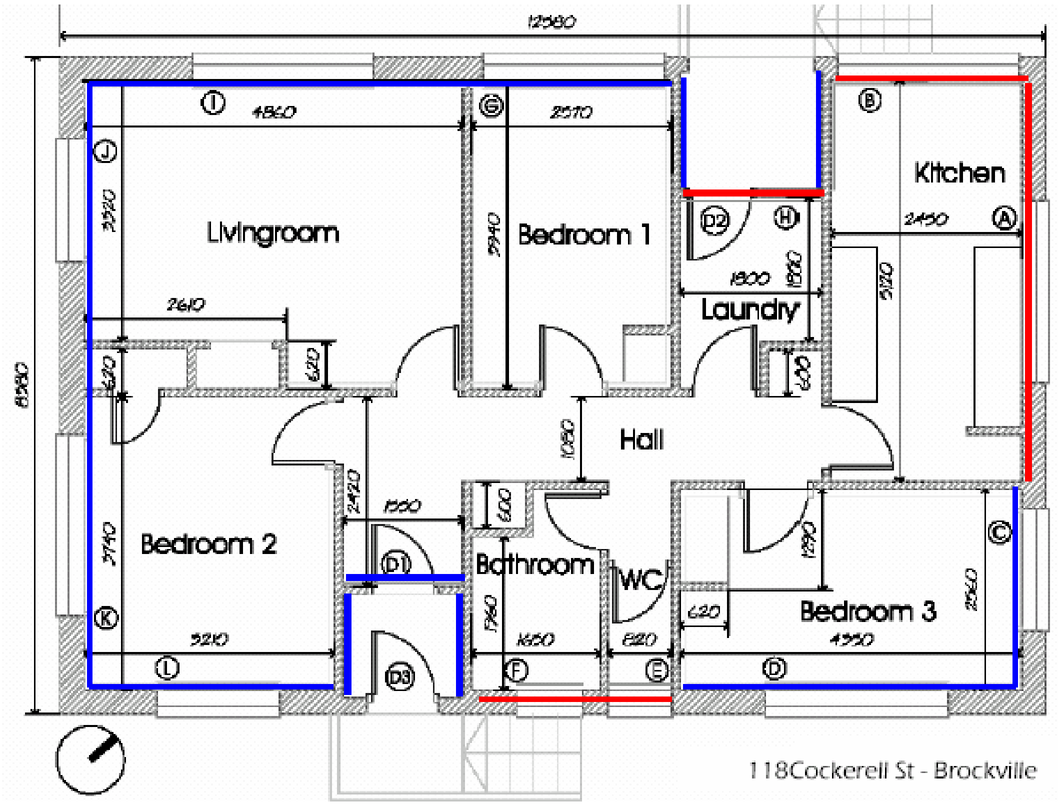
$$Q_T = 0.33 \text{ ACH Volume} + \frac{A_E \Delta T}{R_L}$$

If Q_T can be measured and all other variables are known, R_L can be determined.

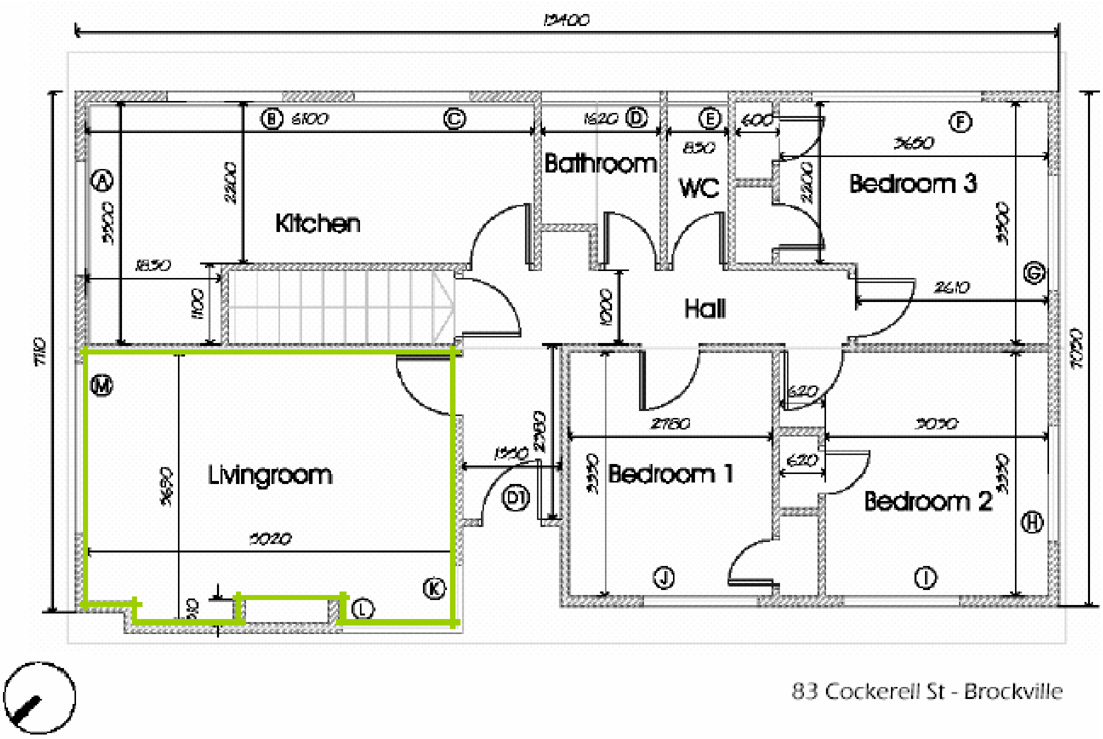
To provide a known Q_T we provided measured constant electrical space heating to the houses. This was done over relatively long periods of time (i.e. 16 hours) to achieve a steady state indoor temperature (i.e. as close as possible to thermal equilibrium). Such equilibrium is only possible if the ambient temperature was constant (or at least relatively constant) and so the experiments could only be carried out during selected nights when this condition was obtained. The equilibrium temperature was chosen as high as possible, (limited by safely issues and the electrical power supply to the house) in order that errors in ΔT were minimised. Indoor and outdoor temperature were measured to assess when equilibrium was reached

Appendix B

Houses Layout (not to scale)



House 1: 118 Cockerell St., Brockville, Dunedin



House 2: 83 Cockerell St., Brockville, Dunedin

Appendix C

		COST			CO_2		
		Initial	Operational		Operational		
Upgrade		Cost	Fuel Cost Reduction	Ratio	CO2 Reduction	CO2 % reduc	Ratio
H1-A BASE		Initial cost	**From Base $3,975**	Initial cost/ annual cost	**From Base 167535**		Initial cost/ annual CO2
STEP 1	S1 add AIRTIGHNESS	$1,000	-$145	1.12	-6,104	4%	6.10
	S1 add CEILING INSULFLUF	$616	-$934	**11.71**	-39,357	23%	63.89
	S1 add CEILING INSULFLUF & POLYESTER	$1,854	-$1,160	4.83	-48,907	29%	26.39
	S1 add CEILING POLYESTER	$1,238	-$1,102	6.88	-46,448	28%	37.53
	S1 add FLOOR EPS	$1,986	-$545	2.12	-22,948	14%	11.56
	S1 add FLOOR FOIL	$649	-$403	4.80	-16,986	10%	26.17
	S1 add HEAT FLUED GAS	$3,320	-$2,144	4.99	-164,383	98%	49.51
	S1 add HEAT HP	$3,199	-$3,181	7.68	-166,341	99%	52.00
	S1 add HEAT MB	$3,529	-$3,058	6.69	-158,613	95%	44.95
	S1 add HEAT PELLETFIRE	$4,034	-$2,674	5.12	-167,327	100%	41.48
	S1 add HEAT WB	$3,529	-$2,413	5.28	-167,535	100%	47.47
	S1 add WALLS FORMALINER	$5,342	-$567	0.82	-23,905	14%	4.47
	S1 add WALLS REGIB	$4,427	-$550	0.96	-23,187	14%	5.24
	S1 add WINDOWS DBL_GLAZE	$10,925	-$257	0.18	-10,821	6%	0.99
	S1 add WINDOWS DRAPES	$3,960	-$167	0.33	-7,046	4%	1.78
	S1 BASE	$0	0		0	0%	
Upgrade		**Cost**	**Fuel Cost Reduction**	**Ratio**	**CO2 Reduction**	**CO2 % reduc**	**Ratio**
H1-B BASE			**From Base $3,041**		**From Base 128178**		
STEP 2	S2 add AIRTIGHNESS	$1,000	-$151	1.16	-6,355	5%	6.35
	S2 add CEILING POLYESTER	$1,238	-$227	1.41	-9,551	7%	7.72
	S2 add FLOOR EPS	$1,986	-$569	2.21	-23,967	19%	12.07
	S2 add FLOOR FOIL	$649	-$420	**5.00**	-17,720	14%	27.30
	S2 add HEAT FLUED GAS	$3,320	-$1,641	3.82	-125,767	98%	37.88
	S2 add HEAT HP	$3,199	-$2,434	5.87	-127,265	99%	39.78
	S2 add HEAT MB	$3,529	-$2,340	5.12	-121,352	95%	34.39
	S2 add HEAT PELLETFIRE	$4,034	-$2,046	3.92	-128,019	100%	31.74
	S2 add HEAT WB/ELECT 50/50	$3,529	-$1,680	3.68	-127,919	100%	36.25
	S2 add WALLS FORMALINER	$5,342	-$593	0.86	-24,972	19%	4.67
	S2 add WALLS REGIB	$4,427	-$575	1.00	-24,218	19%	5.47
	S2 add WINDOWS DBL_GLAZE	$10,925	-$268	0.19	-11,277	9%	1.03
	S2 add WINDOWS DRAPES	$3,960	-$174	0.34	-7,337	6%	1.85
	S2 BASE (now with insulfluf)	$0	$0		0	0%	
Upgrade		**Cost**	**Fuel Cost Reduction**	**Ratio**	**CO2 Reduction**	**CO2 % reduc**	**Ratio**
H1-BB BASE			**From Base**		**From Base**		
STEP 3	S3 add AIRTIGHNESS	$1,000	-$68	0.52	-13	5%	0.01
	S3 add CEILING POLYESTER	$1,238	-$101	0.63	-19	7%	0.02
	S3 add FLOOR EPS	$1,986	-$255	0.99	-48	19%	0.02
	S3 add FLOOR FOIL	$649	-$188	**2.24**	-36	14%	0.06
	S3 add HEAT FLUED GAS	$3,320	$39	-0.09	2,152	**-831%**	-0.65
	S3 add HEAT HP	$3,199	-$754	1.82	654	**-253%**	-0.20
	S3 add HEAT MB	$3,529	-$660	1.44	6,567	**-2534%**	-1.86
	S3 add HEAT PELLETFIRE	$4,034	-$366	0.70	-100	39%	0.02
	S3 add WALLS FORMALINER	$5,342	-$265	0.38	-50	19%	0.01
	S3 add WALLS REGIB	$4,427	-$257	0.45	-49	19%	0.01
	S3 add WINDOWS DBL_GLAZE	$10,925	-$120	0.08	-23	9%	0.00
	S3 add WINDOWS DRAPES	$3,960	-$78	0.15	-15	6%	0.00
	S3 add HEAT WB/ELECT 50/50	$3,529	$0	0.00	0	0%	0.00
	S3 add HEAT WB/HP 50/50	$3,199	-$439	1.06	-154	59%	0.05
	S3 BASE (now with WB/elect)	$0	$0		0	0%	
Upgrade		**Cost**	**Fuel Cost Reduction**	**Ratio**	**CO2 Reduction**	**CO2 % reduc**	**Ratio**
H1-C BASE		$0	**From Base $1,260**		**From Base 240**		
STEP 4	S4 add AIRTIGHNESS	$1,000	-$68	0.53	-13	5%	0.01
	S4 add FLOOR EPS	$1,986	-$258	1.00	-49	20%	0.02
	S4 add FLOOR FOIL	$649	-$191	**2.27**	-36	15%	0.06
	S4 add HEAT FLUED GAS	$3,320	$36	-0.08	1,992	**-831%**	-0.60
	S4 add HEAT HP	$3,199	-$698	1.68	606	**-253%**	-0.19
	S4 add HEAT MB	$3,529	-$611	1.34	6,078	**-2534%**	-1.72
	S4 add HEAT PELLETFIRE	$4,034	-$339	0.65	-92	39%	0.02
	S4 add WALLS FORMALINER	$5,342	-$269	0.39	-51	21%	0.01
	S4 add WALLS REGIB	$4,427	-$260	0.45	-50	21%	0.01
	S4 add WINDOWS DBL_GLAZE	$10,925	-$121	0.09	-23	10%	0.00
	S4 add WINDOWS DRAPES	$3,960	-$79	0.15	-15	6%	0.00
	S4 add HEAT WB/ELECT 50/50	$3,529	$0	0.00	0	0%	0.00
	S4 add HEAT WB/HP 50/50	$3,199	-$406	0.98	-142	59%	0.04
	S4 BASE (now ceiling polyester)	$0	$0		0	0%	

Step	Upgrade	Cost	Fuel Cost Reduction	Ratio	CO2 Reduction	CO2 % reduc	Ratio
	H1-D BASE	$0	**From Base $1,070**		**From Base 204**		
STEP 5	S5 add AIRTIGHNESS	$1,000	-$70	0.54	-13	7%	0.01
STEP 5	S5 add HEAT FLUED GAS	$3,320	$31	-0.07	1,691	**-831%**	-0.51
STEP 5	S5 add HEAT HP	$3,199	-$592	1.43	514	**-253%**	-0.16
STEP 5	S5 add HEAT MB	$3,529	-$518	1.13	5,159	**-2534%**	-1.46
STEP 5	S5 add HEAT PELLETFIRE	$4,034	-$288	0.55	-78	39%	0.02
STEP 5	S5 add WALLS FORMALINER	$5,342	-$275	0.40	-52	26%	0.01
STEP 5	S5 add WALLS REGIB	$4,427	-$267	0.47	-51	25%	0.01
STEP 5	S5 add WINDOWS DBL_GLAZE	$10,925	-$124	0.09	-24	12%	0.00
STEP 5	S5 add WINDOWS DRAPES	$3,960	-$81	0.16	-15	8%	0.00
STEP 5	S5 add HEAT WB/ELECT 50/50	$3,529	$0	0.00	0	0%	0.00
STEP 5	S5 add HEAT WB/HP 50/50	$3,199	-$345	**0.83**	-121	59%	0.04
STEP 5	S5 BASE (now foil added)	$0	$0		0	0%	
	Upgrade	**Cost**	**Fuel Cost Reduction**	**Ratio**	**CO2 Reduction**	**CO2 % reduc**	**Ratio**
	H1-E BASE	$0	**From Base $725**		**From Base 83**		
STEP 6	S6 add WINDOWS DBL_GLAZE	$10,925	-$84	0.06	-10	12%	0.00
STEP 6	S6 add WINDOWS DRAPES	$3,960	-$55	0.11	-6	8%	0.00
STEP 6	S6 add WALLS FORMALINER	$5,342	-$187	0.27	-21	26%	0.00
STEP 6	S6 add WALLS REGIB	$4,427	-$181	0.32	-21	25%	0.00
STEP 6	S6 add HEAT PELLETFIRE	$4,034	$58	-0.11	42	-51%	-0.01
STEP 6	S6 add HEAT MB	$3,529	-$173	0.38	5,279	**-6376%**	-1.50
STEP 6	S6 add HEAT HP	$3,199	-$247	0.60	635	**-767%**	-0.20
STEP 6	S6 add HEAT FLUED GAS	$3,320	$376	-0.87	1,811	**-2188%**	-0.55
STEP 6	S6 add AIRTIGHNESS	$1,000	-$47	**0.37**	-5	7%	0.01
STEP 6	S6 BASE (now wb/hp added)	$0	$0		0	0%	
	Upgrade	**Cost**	**Fuel Cost Reduction**	**Ratio**	**CO2 Reduction**	**CO2 % reduc**	**Ratio**
	H1-F BASE	$0	**From Base $677**		**From Base 77**		
STEP 7	S7 add WINDOWS DBL_GLAZE	$10,925	-$85	0.06	-10	13%	0.00
STEP 7	S7 add WINDOWS DRAPES	$3,960	-$55	0.11	-6	8%	0.00
STEP 7	S7 add WALLS FORMALINER	$5,342	-$188	**0.27**	-22	28%	0.00
STEP 7	S7 add WALLS REGIB	$4,427	-$183	**0.32**	-21	27%	0.00
STEP 7	S7 add HEAT PELLETFIRE	$4,034	$54	-0.10	40	**-51%**	-0.01
STEP 7	S7 add HEAT MB	$3,529	-$162	0.35	4,934	**-6376%**	-1.40
STEP 7	S7 add HEAT HP	$3,199	-$231	0.56	593	**-767%**	-0.19
STEP 7	S7 add HEAT FLUED GAS	$3,320	$351	-0.82	1,693	**-2188%**	-0.51
STEP 7	S7 BASE (now airtighness added)	$0	$0		0	0%	
	Upgrade	**Cost**	**Fuel Cost Reduction**	**Ratio**	**CO2 Reduction**	**CO2 % reduc**	**Ratio**
	H1-G BASE	$0	**From Base $494**		**From Base 57**		
STEP 8	S8 add WINDOWS DBL_GLAZE	$10,925	-$88	**0.06**	-10	18%	0.00
STEP 8	S8 add WINDOWS DRAPES	$3,960	-$57	**0.11**	-7	12%	0.00
STEP 8	S8 add HEAT PELLETFIRE	$4,034	$39	-0.08	29	**-51%**	-0.01
STEP 8	S8 add HEAT MB	$3,529	-$118	**0.26**	3,603	**-6376%**	-1.02
STEP 8	S8 add HEAT HP	$3,199	-$169	0.41	433	**-767%**	-0.14
STEP 8	S8 add HEAT FLUED GAS	$3,320	$256	-0.60	1,236	**-2188%**	-0.37
STEP 8	S8 BASE (now walls/regib added)	$0	$0		0	0%	

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