The Effect of Mandatory Insulation on Household Energy Consumption

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Abstract

Insulation has been required in all new houses in New Zealand since 1978, intended to improve energy efficiency, reduce energy consumption and expenditure, and improve comfort and health. Information from the Household Energy Enduse Project (HEEP) is used to compare energy and temperatures in houses built before and after the mandatory requirements to find out how insulating houses has affected energy consumption and temperatures. On its own, insulation has been shown to be associated with less energy consumption. However, increases in heating temperatures, and the larger floor area of newer houses, have taken up some or all of the potential energy savings. There are major differences in the energy reductions depending primarily on the heating type, with little or no overall reductions in electricity consumption, but significant reductions in other fuels. The implications for retrofitting insulation as an energy conservation measure are discussed.

Keywords: energy efficiency, insulation, retrofit, HEEP, energy conservation

1. Introduction and review

In an effort to improve comfort and reduce energy demand and the cost of space heating, since 1978 all new houses in New Zealand have been required to be insulated. So far in New Zealand there has been little research on the effects of this insulation requirement.

The 1971/72 study by the Department of Statistics compared two groups of houses; one group insulated and the other uninsulated (Department of Statistics, 1976). However, it found that energy use was actually higher in the insulated group, although houses in this group were more likely to be in the colder climate of the South Island and were heated to a higher level. Since insulation was not required at the time it is possible that the houses that were insulated had this work carried out because the occupants wanted to heat the house extensively –a self-selected group.

A retrofit study by BRANZ on one staff house found that adding insulation increased indoor temperatures by about 1.4°C in winter, with a reduction in energy use of 300-400 kWh (Cunningham, Roberts and Hearfield, 2001). Another retrofit study by BRANZ on a selection of Wellington City Council owned pensioner flats showed increased indoor temperatures, improved comfort, and less heating energy use (Cunningham, 2000).

The Health and Housing study conducted by the Otago School of Medicine was designed to measure the effects on respiratory health and health care (e.g. hospital admissions, GP visits) from the retrofit of insulation (Howden-Chapman, Matheson, Crane, Viggers et al., 2007). Temperatures were also measured and some limited information on energy use was collected (electricity and gas billing records, self-reported LPG, wood and coal purchase). Analysis of this information showed that during the winter period temperatures in the bedroom increased after the retrofit of insulation by 0.5°C. Metered total electricity and gas consumption (from billing records) in the intervention houses was 8% less than in the control houses, and 19% less with self-reported LPG, wood and coal usage included. The energy data was not of high quality.

The Department of Physics, University of Otago undertook a study of 111 Housing New Zealand Corporation houses in Southland, where they retrofitted insulation and some other energy-efficiency measures (Lloyd and Callau, 2006). Total electricity consumption was reduced by 5–9%, and 24 hour temperatures increased by 0.6° in winter. The total energy reductions were higher, but the variation in non-electricity consumption was too high to make this result significant. Most of the houses already had some ceiling insulation which substantially reduced the improvement in whole-house heat losses achieved.

In overview, all of these New Zealand studies have shown that retrofitting thermal insulation results in winter indoor temperature increases of 0.5°C to 1.4°C, and small or no savings in energy consumption (although electricity was often the only fuel monitored). However, most of these studies were carried out on particular groups of people (e.g. elderly pensioners in council flats, low income households with low health status, Housing New Zealand clients in Southland) so these studies are not representative of New Zealand as a whole.

Most developed countries have introduced mandatory insulation requirements, with many precipitated by the oil shocks of the 1970s. However, there seems to be a lack of research on the effects of these mandatory insulation requirements.

Shorrock and Utley (2003) tracked energy use and thermal comfort in domestic buildings in the UK. The method used surveyed data on appliance types, efficiencies, and house thermal characteristics, and then modelled the temperature that would be required to give energy consumption equal to the known total energy consumption for the domestic sector. From 1970 to 2000 the average temperatures were modelled to increase by 6.2°C, and the penetration of central heating increased from 31% to 90%, but with the improved efficiency of heating systems and improvements to the house insulation energy consumption per house decreased by about 4%. This result is partly due to increasingly stringent Building Regulations for new houses, and partly due to the upgrade of existing houses. While the effect on new houses alone cannot be estimated from this report, it is clear that most of the potential savings have been taken up in increased temperatures and heating.

2. Data

The Household Energy End-use Project (HEEP) is a nationwide New Zealand study of energy use in approximately 400 households (Isaacs, Camilleri, French, et al., 2010). Analysis of the HEEP houses can be used to quantify the differences in energy use and space heating between pre- and post-1978 houses.

2.1 Heat losses and floor area

All the available HEEP houses have been modelled in ALF3 (Stoecklein and Bassett, 1999) to estimate their space heating requirements and heat loss. The required input data were taken from house plans and audit information collected when the monitoring equipment was installed. This was reported in Isaacs, Camilleri, French, et al., 2010.

No clear cut distinction was found between the whole-house heat losses of pre- and post-1978 houses (**Error! Reference source not found.**), although the average heat loss of the post-1978 houses (482 W/°C) is lower than the pre-1978 houses (586 W/°C). The differences are more pronounced in ***Figure 2*** for the heat loss per m² where most post-1978 houses have a heat loss of <4 W/(m²·°C), but most pre-1978 houses have a heat loss of >4 W/(m²·°C).

The post-1978 houses have lower average heat losses but are larger in floor area than pre-1978 houses (Table 1). If these houses were heated to the same temperatures and extent (which they are clearly not) then they would require about 20% less energy to heat.

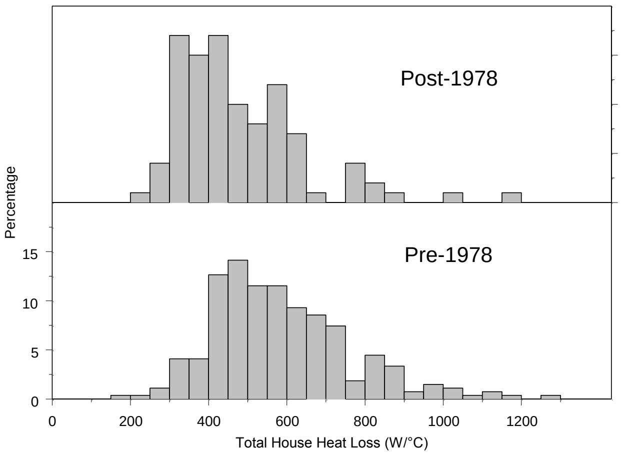

Figure 1: Total house heat loss for pre- and post-1978 houses

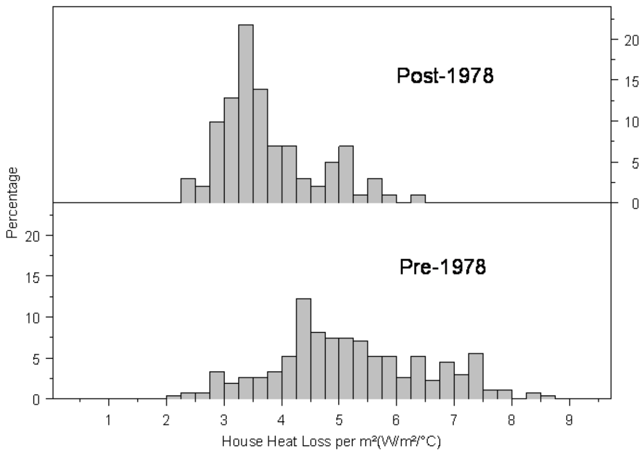

Figure 2: Heat loss per m² for pre- and post-1978 houses

Table 1: Heat losses for pre-and post-1978 HEEP houses

House Period	*Heat loss/m² (W/(m²·°C))*	*SE*	*Total specific loss (W/°C)*	*SE*	*Floor area m²*	*SE*
Pre-1978	*5.2*	*0.1*	*586*	*11*	*119*	*2.5*
Post-1978	*3.8*	*0.1*	*482*	*16*	*132*	*4.6*

2.2 Temperatures and heating pattern

The post-1978 houses are on average 1°C warmer than the pre-1978 houses in the living rooms in winter evenings, and 1.2°C warmer over the whole winter 24 hours, with warmer temperatures for houses with larger heating systems such as natural gas and enclosed solid fuel burners (**Error! Reference source not found.**).

Table 2: Average winter temperatures by heating type

House Period	*Main fuel*	*Mean living evening temp °C*	*SE*	*Mean living 24 hour temp °C*	*SE*
Pre-1978	*Electricity*	*16.8*	*0.3*	*15.0*	*0.3*
Post-1978		*18.6*	*0.3*	*16.9*	*0.3*
Pre-1978	*LPG*	*16.8*	*0.3*	*14.8*	*0.2*
Post-1978		*17.7*	*0.3*	*16.1*	*0.3*
Pre-1978	*Natural gas*	*18.2*	*0.4*	*16.2*	*0.4*
Post-1978		*17.8*	*0.9*	*16.0*	*0.8*
Pre-1978	*Solid fuel*	*18.4*	*0.2*	*16.2*	*0.2*

Post-1978		*19.4*	*0.4*	*17.5*	*0.4*

The heating patterns in New Zealand houses observed in HEEP were usually intermittent, localised, and often poorly controlled. Whole house, 24 hour heating was very uncommon (<5% of houses), with evening only heating in only the living area the most common heating pattern. Temperature control was also usually not good, as many heating systems (e.g. solid fuel burners) do not have thermostatic or timer controls, and with intermittent heating there is considerable warm up time.

The HEEP Heat Index is a synthesised measure of house heating patterns based on heating schedules and zones (Isaacs, Amitrano, Camilleri et al., 2003) designed to quantitatively represent these complex heating patterns. Each heating schedule (nominally evening only, morning and evening, all day, 24 hours) is given a weighting, based on the annual loss factors used in ALF3. For each zone and day the heating index multiplier is applied, then multiplied by the number of days of the week that schedule is used. These are then summed for all zones, and the sum of these for all zones gives the heating index. For example, heating living rooms only in the evening gives a Heating Index of 7 (a weight of 1 for 7 days for 1 zone), while heating all zones (living, bedroom, utility) 24 hours a day gives a Heating Index of 84 (a weight of 4 for 7 days for 3 zones). The most common schedule is winter evening living room heating only (which has a Heat Index of 7).

There is no statistically significant difference in the Heating Index between the pre- and post-1978 houses, suggesting they are heated similarly in terms of schedules and zones (Table 3).

Table 3: Comparison of winter temperatures and Heat Index

House Period	*Mean living room winter evening temp (°C)*	*SE*	*Mean living room 24 hr winter temp (°C)*	*SE*	*Heat Index*	*SE*
Pre-1978	*17.6*	*0.2*	*15.6*	*0.1*	*18.1*	*0.7*
Post-1978	*18.6*	*0.2*	*16.8*	*0.2*	*16.8*	*1.3*

2.3 Space heating energy consumption

Space heating estimates were prepared for all the HEEP houses by comparing the summer energy use baseline (Jan-Mar) with the full year energy use, the difference being assumed to be space heating. This was done for electricity and gas. Space heating for portable LPG heaters and solid fuel burners was monitored directly for all such appliances. This is a different method to the one used for estimating the space heating for the overall HEEP statistical estimates, as the statistical analysis could only give space heating estimates for groups of houses, not for individual buildings. The average of electric space heating used here is about 25% higher, although electricity is a minor heating fuel. Further information on the methodology is in Isaacs, Camilleri, French et al (2010).

Table 4 compares pre- and post-1978 house use of electric and 'all' (i.e. electric, gas, LPG, solid fuel) space heating. This is net energy – electricity is assumed to be 100% efficient[1], an enclosed solid fuel burner[2] assumed to be 60% efficient, an open fire 15%, and a gas appliance 80% efficient.

Comparing the pre-1978 and post-1978 houses, there is no statistically significant difference between their electric space heating energy usage. However this is seriously confounded by the location of the post-1978 houses, as there are more pre-1978 houses in colder climates. Therefore, merely on the basis of the colder climate they would be expected to use more space heating. There is a statistically significant difference in the "All heating" energy in the post-1978 houses, however there are many possible causes, and these are now explored in detail.

Table 4: Comparison of space heating energy

House Period	*Electric heating (kWh/yr)*	*SE*	*All heating (net) (kWh/yr)*	*SE*
Pre-1978	*1,280*	*100*	*3,180*	*200*
Post-1978	*1,060*	*130*	*2,410*	*310*

3. Statistical models of space heating

Statistical models were used to explore the effects of the various physical and socio-demographic input variables, such as pre-1978 status, floor area, income etc, on net energy consumption. These models can be used to attempt to separate the effects of various independent variables to allow the effect of the pre-1978 status to be compared allowing for confounders.

The process of developing these models involves an element of judgement to decide which of the possible model formulations to use. This decision was guided by the data, the goodness of fit, and common sense. Depending on which model was chosen as the final model the effect of the various terms may differ e.g. one model might give an apparently larger effect of the pre-1978 status than another. Hence the estimates of the effect of various variables on energy consumption should not be interpreted as precise estimates. Standard errors are given for each of the variables, which gives some idea of how precisely that particular model defines them, but a slightly different and equally valid formulation of the model might give a slightly different value.

Unfortunately there are several features of the data that make the use of simple linear models problematic. The residuals (the difference between the actual value and the model prediction) are larger for higher heating energy consumption and they are not normally distributed, and the sample variance increases with the energy consumption. Both these features fail to meet two of the major

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[1] Most electric heating was with resistance heaters, with very few heat pumps.

[2] The method for monitoring solid fuel burners and open fires directly measure the net heat output, so the assumed efficiency does not affect the accuracy of their heat output.

criteria for the application of a linear model, which are normally distributed sample measurements with constant variance. The Generalised Linear Model (GLM)[3] is an extension of linear models that can accommodate such statistical distributions by using a non-normal distribution for the sample measurements (e.g. a logarithmic or gamma distribution). They can also fit the data in a non-linear sense by using link functions such as logarithm, inverse or others. These features of the GLM allow the actual underlying structure of the data to be considered in the model and resolve the previous problems noted with the residuals.

The choice of GLM is a matter of finding which type best represents the data. The models used for this analysis use the gamma link function for the statistical distribution of errors, and a logarithmic function to link the predictor to the response. The logarithmic function causes the factors to be multiplicative, not additive as is usual with simple linear models. Overall, these were found to best deal with the non-normal distribution of the residuals and the skewed distribution of the energy consumption.

Statistical models have been created for two different heating energies:

1. Electric space heating only

2. All space heating energy

Although most space heating energy consumption is for non-electric fuels, most houses do use some electric heating (typically in portable electric heaters). As electricity is subject to supply constraints (e.g. peak loads), and some is generated in fossil fuelled power stations, the environmental and supply issues are different to the other fuels (e.g. gas and solid fuel) and it is important to consider the effects of mandatory insulation on electricity alone.

3.1 Electric heating – all houses

There is no significant difference in the national average electric heating energy consumption of the pre- and post-1978 houses (Table 5). However, this takes no account of regional variation or other confounders.

45 houses that used no electric space heating at all were removed from the analysis as the logarithmic transformation of zero is undefined. The final model found the post-1978 houses were associated with (23±15)% less electric space heating, allowing for the confounders of floor area, regional climate, winter heating temperatures, and the type of main heating fuel. The main fuel used for heating (whether electricity, LPG, gas or solid fuel) had a very large effect, associated with a drop of

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[3] See *An Introduction to Generalised Linear Models* (2nd Edition) by AJ Dobson. Chapman and Hall/CRC, New York.

about (45±20)% in electric space heating in houses that mainly use non-electric heating (electric heating is used in most houses, although often only as back-up or secondary heating). The higher temperatures in the post-1978 houses were associated with an increased energy use of about (10±3)% and the larger floor area with a (6±1)% increase. The overall difference between the pre- and post-1978 houses was about (-10±15)%, which is not statistically significantly different from zero.[4]

Table 5: Electric space heating energy and temperature – houses heated mainly with electricity

House period	*Electric heating (kWh/year)*	*SE*	*Mean living room temperature (24 hours) °C*	*SE*
Pre-1978	*2,210*	*260*	*15.0*	*0.2*
Post-1978	*1,470*	*330*	*16.8*	*0.3*

We conclude that there is no significant difference between the amount of electric space heating in the pre- and post-1978 houses, and that the post-1978 houses are achieving higher temperatures over larger floor areas for approximately the same amount of electric heating as the pre-1978 houses, allowing for confounders. If the pre-1978 houses were insulated to the same levels as the post-1978 houses, and heated to the same (higher) temperature, the model predicts that the difference in electric space heating would be (-15±15)%, which again is not statistically significantly different from zero.

Part of the reason for the high statistical uncertainty is the large variation in electric space heating between houses, particularly for those that mainly use other fuels. Looking at houses that mainly heat with electricity should reduce this variation and give a larger difference.

3.2 Electric heating – houses mainly heated by electricity

The analysis was repeated for houses that use electricity as their main means of space heating. Reductions of energy use would be expected to be higher as more electricity is used, and it is used to heat warmer rooms such as living areas instead of being used more often in cooler bedrooms and for occasional heating (Isaacs, Camilleri, French, et al., 2010). This is confirmed as the average electric space heating energy is much lower in the post-1978 houses (Table 5). However, this comparison is seriously confounded by differences in climate, heating temperature and other factors. The final model had independent variables of post-1978 status, floor area, region (representing climate), living room temperature and equivalised income to control for these confounding variables.

The model of the mainly electrically heated houses shows a much larger effect of the post-1978 status on electric space heating – a decrease of (60±25)% in electric space heating. Offsetting these factors were: the higher temperatures – +1.8°C in the post-1978 electrically heated houses and associated

[4] Since these GLMs use exponential functions, the means and standard errors are combined logarithmically. The ratio of standard error to the mean is not used to test for statistical significance; rather the confidence levels generated by the SPLUS GLM models are reported.

with increased electric space heating use of (48±9)%; larger floor areas increasing electric space heating use by about (5±4)%; and higher equivalised incomes[5] associated with an increase in electric space heating use of about (10±4)%.

The net effect of the larger floor areas and higher temperatures of the post-1978 houses is associated with a difference in electric space heating of (-38±27)%, and this is statistically significantly different from zero at a 95% confidence level.[4]

If the mainly electrically heated pre-1978 houses were insulated to the same levels as the post-1978 houses, and heated to the same higher temperature, the model predicts that the difference in electric space heating would be (-41±27)%, which again is statistically significantly different from zero at a 95% confidence level.[4]

Differences in electric space heating energy for houses mainly heated by electricity are quite high. The low indoor temperatures achieved (15°C), and the comparatively small difference between inside and outside temperatures (typically averaging about 4-7°C), means that insulation has a large impact on heating energy use, especially given that internal and solar gains contribute a large proportion of required heating energy.

3.3 All heating fuels – all houses

It has been shown that there are statistically significant differences between pre- and post-1978 houses on a national basis when all heating fuels are considered (electricity, gas, LPG, solid fuel), with the post-1978 houses using less heating energy (Table 4).

A GLM was used to evaluate the effects of the various confounding variables. In isolation the post-1978 status was associated with (45±11)% less space heating energy use. Higher temperatures in the post-1978 houses were associated with an increase in space heating energy use of about (32±3%), and floor area by about (6±1)%.

The net effect of the larger floor areas and higher temperatures of the post-1978 houses is associated with a difference in all fuels space heating of (-23±11)%, and this is statistically significantly different from zero at a 95% confidence level.[4]

If the pre-1978 houses were insulated to the same levels as the post-1978 houses, and heated to the same higher temperature (1.2°C higher), the model predicts that the difference in all fuels space heating would be (-28±11)%, which again is statistically significantly different from zero at a 95% confidence level.[4]

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[5] Higher equivalised incomes are, presumably, not caused by living in a post-1978 house.

4. Summary of model results and discussion

Table 6 summarises the modelling results:

- ‘Post-1978 only’ refers to the % difference in the energy quantity associated with the post-1978 status, allowing for confounders.

- ‘Post-1978, floor area & temp’ are the combined effect of the post-1978 construction, the larger floor area and higher temperatures found in the post-1978 houses, allowing for confounders.

- ‘Pre-1978, post-1978 insulation & temp’ considers the impact if houses built pre-1978 had the same levels of insulation and rooms temperatures as found in post-1978, allowing for confounders.

Note that the differences shown in a bold font in Table 6 are statistically significantly different from zero at the 95% confidence level.

Table 6: Summary of model results

Fuel type	*Quantity*	*House group*	*Post-1978 only (%)*	*Post-1978, floor area & temp (%)*	*Pre-1978, post-1978 insulation & temp (%)*
Electricity	*Heating*	*All houses*	***-23±15***	*-10±15*	*-15±15*
Electricity	*Heating*	*Elect. heated*	***-60±25***	***-38±27***	***-41±27***
All fuels	*Heating*	*All houses*	***-45±11***	***-23±11***	***-28±11***

In all cases, the ‘Post-1978 only’ was associated with a decrease in energy use. This demonstrates with a high degree of confidence that, allowing for confounders, the introduction of mandatory insulation in 1978 has led to improvements in energy efficiency of the housing stock. However, increases in temperatures and larger floor areas in the post-1978 houses have taken up part, and sometimes all, of any potential energy reductions.

The ‘Post-1978, floor area & temp’ results are mixed (Table 6). They give a comparison between the pre-1978 and post-1978 houses allowing for confounders of differences in regional climate, and income and life stage, between the pre-1978 and post-1978 groups. For example, since on average post-1978 houses are in warmer climates, this alone would be expected to reduce space heating energy consumption. With these confounders allowed for it can be seen that the post-1978 houses use less space heating energy for all fuels (Table 6) even though they are on average larger and heated to higher temperatures. However, they use the same amount of electricity (total electricity excluding hot water). The group of mainly electrically heated houses are the only group that show less electric space heating in the post-1978 group compared to the corresponding pre-1978 group.

'Pre-1978, post-1978 insulation & temp' is a prediction from the model of how the energy consumption of pre-1978 houses would change if insulated to the same level as post-1978 houses[6] and heated to the same warmer temperatures. This assumes no change in heating patterns and zones (we have already shown that the pre- and post-1978 houses are heated to about similar patterns and zones). Again, the overall result is mixed, with a similar outcome as the difference between the pre- and post-1978 houses. There are reductions in all fuels for all houses, but no reduction in electricity consumption, except for houses primarily heated by electricity.

In summary, it has been shown that mandatory insulation has led to warmer homes as well as reduced space heating and (total excluding hot water) energy use. However, most of the energy reductions have come from non-electric fuels. The total energy savings for all fuels in the 27% of houses that are post-1978 houses would be about 2–3% of total energy consumption (all fuels), while the total electricity savings in the mainly electrically heated houses (about 8% of households) would be <1% of total electricity consumption.

5. Conclusions

The mandatory insulation of houses in New Zealand since 1978 has resulted in higher indoor temperatures and reduced energy consumption and space heating. Total net energy consumption excluding hot water was (10±6%) lower in the post-1978 houses, however total electricity consumption was not significantly different. Heating energy (all fuels) was (23±11)% lower in the post-1978 houses. Average temperatures in the post-1978 houses were higher, and average floor areas larger, and these factors increased energy consumption. These effects took up ~40% of the potential savings in all fuels, and most or all of the energy savings for electricity.

While the experiment did not retrofit insulation to pre-1978 houses the results give some idea what might be expected. If the pre-1978 houses were insulated to the same levels as the post-1978 houses and heated to the same higher temperatures then the model predicts that total energy consumption of all fuels of these post-1978 houses excluding hot water would be (14±6)% lower, and there would be no significant change for electricity (7±7% lower).

[6] As noted, a pre-1978 house cannot be retrofitted to the same overall insulation level as a post-1978 house of the same design by only installing ceiling and floor insulation. Wall insulation, or double glazing is also required but this is uncommon due to practicality and cost.

Acknowledgments

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