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Evaluation of the Warmer Kiwis Homes Programme:

Full Report including Cost Benefit Analysis

Motu economic & public policy research

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Warmer Kiwi Homes

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Abstract

We evaluate the heat pump component of New Zealand's Warmer Kiwi Homes (WKH) programme. The programme includes provision of heat pumps in living areas for eligible households (based on neighbourhood or income) that do not have suitable heating. It also includes installation of retrofitted insulation for houses with insufficient insulation. Staggered installation enables difference-in-difference estimates of impacts. Heat pump outcomes on which we focus include warmth and dryness of the living area, personal comfort and wellbeing, and electricity consumption. We combine the heat pump findings with prior findings related to insulation and heating to provide a set of cost benefit analyses of WKH. We find that household members overwhelmingly report increases in warmth, comfort and satisfaction with their home, and report decreases in condensation, damp and having to restrict heating due to cost. Some increase in life satisfaction is reported. Living areas of treated houses experience increases in temperature which are most pronounced around breakfast and evening times, and when outdoor temperatures are low. Houses also experience reduced humidity. Households that use the heat pump as an air conditioner experience reduced summer temperatures when outdoor temperatures are high. Winter electricity use falls in a house fitted with a heat pump relative to houses without a heat pump; savings are negligible at night and increase through the day, peaking at 5-9pm. No increase in electricity consumption is detected in summer. Benefit cost ratios (BCRs) are calculated using both wellbeing metrics and conventional health and energy components. The wellbeing-based BCR for the heat pump component (which places a high value on living in a warm home) is estimated at 7.49 while the more conventionally calculated (but overly conservative) BCR is 2.15. For the full WKH programme, the corresponding BCRs are calculated as 4.36 and 1.89.

JEL codes

I18, I31, I38, Q48

Keywords

Heat pumps; indoor temperature; electricity use; wellbeing; Warmer Kiwi Homes

Summary haiku

Houses are warmer

Even in winter and spring

Heat pumps are worth it

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Executive summary[1]

Objectives

The Warmer Kiwi Homes (WKH) programme includes the provision of clean heating devices in living areas for eligible households that do not already have suitable heating. The programme also includes installation of retrofitted insulation for houses without (or with insufficient) insulation. To be eligible, the householder must be an owner-occupier and must either be situated in a disadvantaged neighbourhood or hold a Community Services Card.

This report provides a comprehensive evaluation of the heat pump component of WKH. It analyses the impact of heat pump installation on outcomes for households that received a heat pump through the programme. Outcomes on which we focus include warmth and dryness of the living area, personal comfort and wellbeing, heating and ventilation related behaviours, and electricity consumption. The evaluation combines the heat pump findings with prior findings related to insulation and heating to provide a set of cost benefit analyses of the WKH programme.

Evaluation coverage and components

Our sample for the heat pump analysis comprises 127 WKH participants who applied for a heat pump in 2021 (the 2021 cohort) and a further 37 WKH participants who applied for a heat pump in 2022 (the 2022 cohort). Of the 2021 cohort, 85 remained in the study in 2022 enabling analysis both of heat pump use in a second winter and over a first summer for this cohort. The specific evaluation periods that we cover are “winter” (June – September) 2021, “summer” (February – March) 2022, and “winter” (June – September) 2022. The first winter for each cohort is henceforth referred to as *First winter*, the second winter (for the 2021 cohort) as *Second winter*, and summer 2022 (for the 2021 cohort) as *First summer*.

The evaluation covers all three climate zones as defined by Standards New Zealand (NZS 4218: 2009) with households from: Auckland (zone 1), Waikato and Wellington (zone 2), and Christchurch (zone 3). The houses included in the evaluation cover a diverse set of house types and households.

The study incorporates: linked household survey data (both before and after heat pump installation, and from a subsequent survey for the 2021 cohort at the end of their second winter), an initial house condition report, half-hourly data on indoor environmental outcomes (temperature, humidity and CO_2) and half-hourly data on electricity consumption. The combination of these elements makes this evaluation more comprehensive than any prior evaluation of the impacts of heat pump use in New Zealand or elsewhere. COVID-19 and supply chain issues effectively randomised (from the household perspective) whether and/or when a study house received a heat pump during each of 2021 and 2022. This randomisation resulted in some features of a natural experiment which we have leveraged in our statistical work.

The study's cost benefit analyses are provided for the full WKH programme and for the heat pump and for the insulation components separately. Central estimates – which relate to societal benefits and societal costs – are based on the findings in this study supplemented by external data, each applied to Treasury's CBAx model. In addition, we calculate a fiscal benefit cost ratio that relates solely to state expenditures; this fiscal ratio, however, is not a measure of overall benefits and costs, so is relevant only to internal government fiscal calculations.

Key findings

Analysis across all components of the evaluation indicate a comprehensive set of benefits achieved through installation of WKH heat pumps. Key findings are as follows:

Indoor comfort, wellbeing and heating behaviours

Over *First winter*, for households that had a heat pump installed:

- 77% reported an increase in warmth in the living area;
- 87% reported an improvement in comfort;
- 89% reported a reduction in condensation on living room windows;
- 47% reported a reduction in damp in the living area;
- 81% reported being more satisfied with their home;
- 65% -71% reported a reduction in having to restrict their heating due to cost;
- A net 15% reported an improvement in their overall satisfaction with life (noting that this measure will also have been affected by the 2021 lockdowns and other factors).

These improvements were sustained over *Second winter*: 77% of heat pump recipients in each of the *First winter* and *Second winter* surveys reported a warmer house in winter after receiving their heat pump. Similar sustained gains are documented in householders' responses with respect to comfort, wellbeing and cost reductions.

Indoor environmental quality

- *First winter* living area temperatures show an increase following heat pump installation by an average of 1.1°C relative to a house without a heat pump fitted under WKH.
- Higher temperatures are mirrored, or amplified, in *Second winter* indicating sustained increases in warmth due to the heat pump.
- The indoor temperature gains are highest when outdoor temperatures are low with an estimated indoor temperature gain of 1.9°C when the external temperature is 0°C.
- Indoor temperature gains (relative to outdoor temperatures) are greatest at 'breakfast' time (1.6°C) and at 'dinner/evening' time (1.2°C).
- Draughty houses experience lower gains in indoor temperature with the average gain in a draughty house being 0.9°C compared with 2.1°C for a non-draughty house.
- Installation of a heat pump significantly reduces living area indoor relative humidity and CO_2.
- Houses that used the heat pump as an air conditioner over summer recorded lower indoor temperatures, with the temperature reduction peaking at 6-7pm.

Electricity use

- Electricity use through winter falls in a house fitted with a heat pump by an estimated 16% relative to a house without a heat pump installed.
- Electricity savings are negligible at night and increase through the day, peaking at 5-9pm.
- Peak electricity reductions occur when there are also indoor temperature gains reflecting replacement of previous energy inefficient heaters by more efficient heat pumps.
- Our analysis estimates no significant increase in electricity consumption over summer for houses that use the heat pump as an air conditioner.

Programme satisfaction

Over *First winter*, of households that had a heat pump installed:

- 86% stated that they were very happy or happy with the WKH subsidy programme;
- 85% reported that the heat pump had met or exceeded their expectations;
- 93% considered that the heat pump was the right choice for their home.

Cost benefit analysis

The cost benefit analysis (CBA) provides a comprehensive examination of the benefits and costs of installing a heat pump alongside insulation. Analysis of insulation alone is also provided together with calculation of a BCR (benefit cost ratio) for the full WKH programme (heat pump plus insulation). The CBA is conducted from a societal perspective and includes a wellbeing component. The societal perspective includes costs and benefits accrued across all stakeholders including government, homeowners and employers, as well as wider society (e.g. from reduced carbon emissions). Two alternative societal approaches are adopted to calculate the BCRs. The "wellbeing/energy BCR" is based on a wellbeing measure relating to house warmth from the Treasury CBAx model, plus energy and carbon saving benefits. This measure places considerable weight on living in a warm house. The "health/energy BCR" incorporates health benefits derived from prior evaluations, plus energy and carbon saving benefits. (A fiscal analysis is also included but these measures are not indicative of the programme's societal benefits and costs).

The base case wellbeing/energy BCR for the full WKH programme is estimated to be 4.36. The heat pump component has an estimated wellbeing/energy BCR of 7.49 while the BCR for the insulation component is 3.51. The health/energy BCR for the full WKH programme is 1.89 with the heat pump BCR calculated at 2.15 and the insulation component BCR at 1.78.

Conclusions

The findings of this evaluation indicate that installation of a heat pump through the WKH programme results in households that are more comfortable in their homes, with living areas that are materially warmer and drier in winter. On average, living area temperatures are warmer by 1.1°C during winter for a house with a WKH heat pump fitted relative to one without. These benefits occur at the same time as treated households, on average, reduce their electricity consumption, with reduced electricity use being especially marked in the late afternoon and evening. Households that used their heat pump over summer as an air conditioner also experienced reduced living area temperatures, so increasing their comfort, with no significant increase in electricity consumption.

The benefits experienced by households are reflected in the cost benefit analysis. Our central estimate of the societal benefit cost ratio (BCR) for the WKH heat pump component is 7.49 when our estimates are applied to the wellbeing-based yardsticks in Treasury's cost benefit analysis model (CBAx). Estimates based on more conservative assumptions, which exclude many of the wellbeing gains, show a BCR for WKH heat pump installation of 2.15. Corresponding BCRs for the insulation component are 3.51 and 1.78. For the WKH programme as a whole, the corresponding BCRs are 4.36 and 1.89. Each of the heat pump and insulation components, and the wider WKH programme, are therefore estimated to have societal benefits that considerably exceed their costs.

1: Introduction and Background

Introduction*

This report presents an impact evaluation of the Warmer Kiwi Homes (WKH) programme conducted over 2021 and 2022. The evaluation, funded by EECA and undertaken independently by Motu Research, has collected and analysed new qualitative and quantitative data on the effects of heat pump installation in low income New Zealand housing. The new information provided using the data is combined with information from other sources to construct a cost benefit analysis (CBA) of the WKH programme. The CBA is conducted for: (i) the heat pump component of the programme, (ii) the insulation component of the programme, and (iii) the complete programme comprising the heat pump and insulation components. The CBA is conducted at the societal level; we also provide estimates that are relevant at the fiscal level (i.e. related to government financial flows).

This study is the second of two phases of evaluation of the programme. Phase 1 reviewed prior studies on clean heating and insulation from New Zealand and international sources and identified evidence gaps.[2] This led to the commissioning of Phase 2, the 'Warmer Kiwis Study', which includes new primary research focused on the heat pump component of the programme. Interim results from this second phase were published in January 2022 (henceforth referred to as the *Interim Report*) covering data gathered over the first winter of the evaluation (June to September 2021).[3] The evaluation was initially designed to be conducted just through 2021 but was extended to include 2022 because of COVID-19 and supply chain complications in 2021, and to extend data gathering to monitor households for a longer time span.

The current document covers the full evaluation that includes analysis of data gathered from June 2021 to September 2022. The extension to September 2022 means that we include analysis of effects over two winters plus a summer for the first cohort of houses in the study that were fitted with heat pumps in 2021. (We refer to these houses as the 2021 cohort.) The extension includes a second cohort of houses that were first included in the study in 2022 (the 2022 cohort); the latter houses have data pertaining to a single winter. Analysis is conducted for three separate 'seasons': *First winter* (defined as June-September 2021 for the 2021 cohort and as June-September 2022 for the 2022 cohort), *Second winter* (defined as June-September 2022 for the 2021 cohort), and *First summer* (defined as February-March 2022 for the 2021 cohort). June is officially the first month of winter, while September (despite being officially defined as spring) is also a cold month, so is

* All notes in the document are included as endnotes.

grouped with the other winter months.[4] Summer is officially defined as December-February, but we include March (which is a warm month) and exclude December and January as many households take vacation over these months which is likely to lead to noisy data.[5]

An accompanying Summary report includes key points from the analysis in this Full Report plus the cost benefit analysis. Box 1 shows the full set of reports that comprise the WKH evaluation.

Box 1: An overview of the Warmer Kiwi Homes evaluation programme

Phase 1: Desk based review (2020)

Objectives

- Benefit: Cost Ratio estimated from similar programmes conducted in New Zealand and Internationally.
- Summary of evidence gaps and opportunities to gather new data within an evaluation of WKH.

Phase 2: Warmer Kiwis Study (2021/22)

Objectives

- Measure impacts on health and wellbeing, indoor environment and change in electricity use.
- Updated Benefit: Cost ratio for Warmer Kiwi Homes

Interim Report (January 2022)

- Initial findings from monitoring of 127 homes in the first winter after having a heat pump installed.
- Covers the monitoring period June-September 2021.

Final (Full and Summary) Reports (December 2022)

- Include data from technical assessments of the effects of having a heat pump covering the extended sample of 164 homes, with a subset of homes monitored over two winters plus one summer.
- Cost benefit analysis of Warmer Kiwi Homes programme.

Background

The World Health Organization (WHO) recommends a minimum indoor temperature of 18°C,[6] a standard that many New Zealand houses fail to meet.[7] In the 2018 New Zealand census, 21.2% of homes were described as "*too cold*" by occupants and 21.5% were described as "*damp*".[8] Cold houses are more prone to indoor dampness, with moisture condensing on cold surfaces such as walls and windows.

There is clear evidence in New Zealand of cold, damp housing contributing to poor health and wellbeing outcomings.[9] Negative health impacts of poor quality (cold, damp and mouldy) housing arise from exposure to lower indoor temperatures that contribute to increased damp and mould. The health impacts include increased risk of respiratory infection, asthma exacerbation and potentially also asthma development.[10] A 2007 analysis calculated a 21% attributable fraction of asthma cases result from dampness and mould.[11] Existing poor-quality heaters may also contribute to raised levels of nitrogen dioxide and other harmful particulates plus avoidable greenhouse gas emissions.

A BRANZ study found that houses kept at temperatures of between 18°C and 20°C could avoid indoor dampness.[12] A potential cause of cold and damp prone housing is inadequate or ineffective heating. In addition to the low levels of insulation in older houses, New Zealanders traditionally only heat main living areas and approximately one tenth of homes have no heating source or rely on portable gas heaters for warmth.[13] Evidence also shows that indoor dampness is related to characteristics of the house: Taptiklis et al. (2022) analysed New Zealand House Survey Condition data (from 2005-2015) showing that subfloor and building envelope defects were associated with (inspector-assessed) dampness and objectively measured moisture in floor joists. In addition, poorer insulation, poor ventilation and higher occupancy were associated with increased (inspector assessed) subjective dampness in the home.[14]

Warmer Kiwi Homes (WKH) is a government scheme run by EECA (Energy Efficiency Conservation Authority).[15] It has the primary objective of making New Zealand homes warmer, drier, and healthier, with a secondary objective of improving the energy efficiency of homes. Improving energy efficiency of houses can contribute to some combination of (i) reduced energy use for a given indoor temperature, and (ii) increased indoor temperatures for given energy use.[16] The first aspect contributes to a reduction of carbon emissions and to alleviation of 'energy hardship';[17] the second to improved health outcomes. The WKH programme is designed to help low-income owner-occupiers overcome financial barriers to energy efficiency by providing insulation and clean, effective, efficient heating to the main living area at low or no cost to the homeowner. Two core aspects of the programme are:

(i) Providing retrofitted insulation to older houses with insufficient existing insulation.

(ii) Providing clean heating devices to living areas in houses that do not have such heating already in place.

In practice, most clean heating devices fitted within the WKH programme are heat pumps.[18] The scheme is available to homeowners where the house is located in a more deprived area (NZDep = 8, 9 or 10) or in which the homeowner holds a Community Services Card (CSC) which is available to those on low incomes. Homes which receive a heater must also have been insulated first, either through the Warmer Kiwi Homes programme or independently.

The Phase 1 WKH report identified that considerable evidence exists to support positive effects of retrofitted insulation in the New Zealand context.[19, 20] Much of this evidence relates to prior evaluation of the Warm-Up New Zealand: Heat Smart (WUNZ:HS) retrofit programme.[21] Fyfe et al. (2020) extended previous health-related evaluations of this programme finding that retrofitted insulation reduced hospital admission rates, especially for respiratory disease, asthma and ischaemic heart disease in people aged over 65 years.[22] Fyfe et al. (2022) further showed that retrofitted insulation reduced both the incidence and severity of chronic respiratory disease.[23]

Based primarily on benefits from retrofitted insulation, the Phase 1 report concluded that the WKH scheme had, as a central estimate, a benefit cost ratio (BCR) of 4.66; i.e. $4.66 worth of benefits for every $1 spent. This estimate excluded benefits relating to improved comfort and wellbeing following a retrofit. The report concluded that there was less thorough evidence regarding the net benefits of installing heat pumps as part of a retrofit programme, and the evidence that was available was conflicting. [24, 25, 26, 27, 28, 29, 30, 31]

Since the Phase 1 report, several new studies have been published based on retrofit programmes in other countries that are relevant to the evaluation. Analysing the link between fuel deprivation and life satisfaction, Davillas et al.[32] show that subjective wellbeing is associated with energy hardship. Based on this study, we might therefore expect to observe a link between the WKH heat pump intervention and householders' wellbeing if retrofitted heat pumps lead to improved energy efficiency in the home.

Several studies indicate that benefits of a heating intervention may depend on contextual factors relating to household type, house characteristics,[33] the environment, and the scheme itself.[34] For instance, a recent UK study[35] of a first-time central heating intervention for lower income households (most of whom were homeowners) found that the intervention group reported improvements in the indoor environment, finances, and mental well-being. However, responses differed across participants, reflecting diverse resident and housing characteristics. Similarly, an assessment of a retrofit scheme in Ireland[36] found persistence of behaviours affecting energy use following a retrofit which had the potential to cancel out some of the savings made through retrofitting. The authors of that study argued for an integrated approach that combines a housing retrofit with a programme to re-shape householders' energy use practices.

An interim evaluation of the UK's Warmer Homes Fund (WHF),[37] which is designed to reduce fuel poverty, includes effects of 'category 2' interventions for rural homes, some of which (but not all) include heat pumps. (The heat pump intervention is not differentiated from other 'category 2' interventions that include LPG-based solutions.) Based on questionnaires, 82% of category 2 respondents reported being able to keep their whole homes warm when it was cold outside compared with 16% before the intervention. Furthermore, 46% of category 2 respondents stated that it was easier to afford their energy bills after the intervention, compared with 16% who found it more difficult to afford those bills. In terms of health, 59% of category 2 respondents reported better physical health after the intervention and 44% reported better mental health.

Another UK intervention designed to reduce fuel poverty was undertaken in East Sussex over 2016 to 2018 with heating and/or insulation installed in 149 homes.[38] Unlike the WKH programme, the majority of these interventions comprised new boilers or new central heating systems (32.2%). The results are instructive: Householders' self-rated health and wellbeing were significantly higher post-installation and interviewees reported fewer chest infections, reduced pain, feeling less anxious and depressed, and feeling happier and more relaxed. These benefits were accompanied, in many cases, by a reported reductions in energy bills.

These findings from policy interventions regarding cold homes in the UK are consistent with findings from a recent study using data from the UK Household Longitudinal Survey.[39] That study found (after controlling for initial mental distress) that moving into a cold home is associated with almost double the odds of experiencing severe mental distress for those who initially had no mental distress, and over three times the odds of severe mental distress for those previously on the borderline of severe mental distress.

Barrington-Leigh et al.[40] examined a retrofit programme in China that subsidises heat pumps and electricity while banning coal. They found that households in higher income districts eliminated coal use with benefits for indoor temperature, indoor air pollution, and life satisfaction. However, there was only partial effectiveness of the programme in lower income districts. The authors concluded that extra support for the less affluent is essential in order to make such a scheme effective in poorer areas.

Perhaps the most similar evaluation of a programme to this WKH evaluation is that of Sustainability Victoria examining impacts of the Victorian Healthy Homes Program.[41] The programme comprised a randomised control trial of approximately 1,000 low-income households in Victoria (each of which had a health or social care need). Treated houses received retrofits (designed by experts but subject to an overall price cap) across multiple dimensions. Approximately half the treated houses received a new heat pump (reverse cycle air conditioner), but gas remained the main form of heating for many of the households. Results were not split according to treatment type (e.g. heat pump versus other forms of upgrade). Average indoor temperature for treated houses increased by 0.33°C, with increases particularly strong in the morning; exposure to temperatures of less than 18°C was reduced by 43 minutes per day. Treated householders were more than twice as likely as controls to report that their home felt warmer over winter and they reported reduced condensation. The study found that these gains were obtained despite a significant reduction in gas use in upgraded homes, with no significant change in electricity use. Significant health benefits were reported, including reduced breathlessness and improved quality of life, particularly for mental health. Aggregating benefits over a 10 year period, a cost benefit analysis (CBA) showed a benefit: cost ratio of 2.7, with the bulk of benefits coming through health-related avenues.

Together, the New Zealand and international research implies that policy initiatives which encourage more efficient heating with improved thermal comfort are likely to result in overall societal benefits. The science of evaluating the monetary equivalent value of some of these benefits (so that they can be included in a CBA) is, however, still in its infancy. A recent New Zealand contribution is that of Smith and Davies[42] which is based on Stats NZ data gathered through the General Social Survey (a randomly sampled survey of approximately 8,000 New Zealand adults, with a response rate of around 80%). Smith and Davies use cost-wellbeing techniques to value benefits attributable to various housing characteristics. Cost-wellbeing analysis is an extension of cost benefit analysis in which benefits of an intervention are assessed using their contribution to a person's subjective wellbeing (measured by their response to a question on overall life satisfaction) together with an estimate of the monetary-equivalent value of this change in subjective wellbeing. Across the full population, the study estimates that a household having "some" mould incurs a (non-monetary) cost (relative to having no mould) that is equivalent to an annual income loss of between $2,164 and $6,749; "very bad" household mould incurs a cost of $3,353 to $9,878. Corresponding ranges for costs of a house being considered "sometimes" cold is $3,591 to $10,458, while the cost of being "often or always" cold is estimated at $5,429 to $14,457.[43] Each of these ranges is wide, indicating considerable uncertainty in the monetary equivalent wellbeing effects of having a cold or mouldy house. Smith and Davies also estimate costs of mental and physical health. It is important not to double count benefits, so in our attribution of wellbeing benefits, we count only temperature benefits, since the temperature benefits are likely to influence each of mould, mental health and physical health. In our application of these estimates, we adopt the figures based on Smith and Davies that are incorporated into the Treasury's CBAx model.[44]

Given the findings summarised above, it is the case that there are still few studies of the specific benefits attributable to fitting heat pumps (as opposed to other heating devices) within a housing retrofit scheme. Our focus, in this evaluation of the heat pump component of the WKH programme, is to understand how heat pumps have contributed to occupants' heating behaviours, wellbeing and comfort, their electricity use, and to indoor environmental outcomes including temperature, relative humidity and CO_2 in the living area. The eligibility criteria for WKH participation means that this study is applicable to homeowners living in poorer areas or who are on lower incomes. Being homeowners, most recipients will not be amongst the most disadvantaged in society but the other eligibility criteria imply that most will also not be amongst the most advantaged.

Report structure

Section 2 outlines the nature and methods used in the evaluation. The study includes information gathered from specially designed household surveys, indoor environmental monitors placed in participants' living areas, and electricity records. The section also outlines practical issues which arose through 2021 (and, to a lesser extent, 2022) that provided logistical challenges to the evaluation. The methods used to address these challenges are outlined. Section 3 details the characteristics of houses and households that are included in the evaluation. This information was gathered through the household surveys and through an initial house inspection for WKH participants. Section 4 presents results based on information gathered from the household surveys, the internal environmental monitors and from the electricity records. Section 5 provides the methods, data and outcomes of the CBAs relating to the WKH programme. Conclusions and opportunities for additional analysis are presented in section 6.

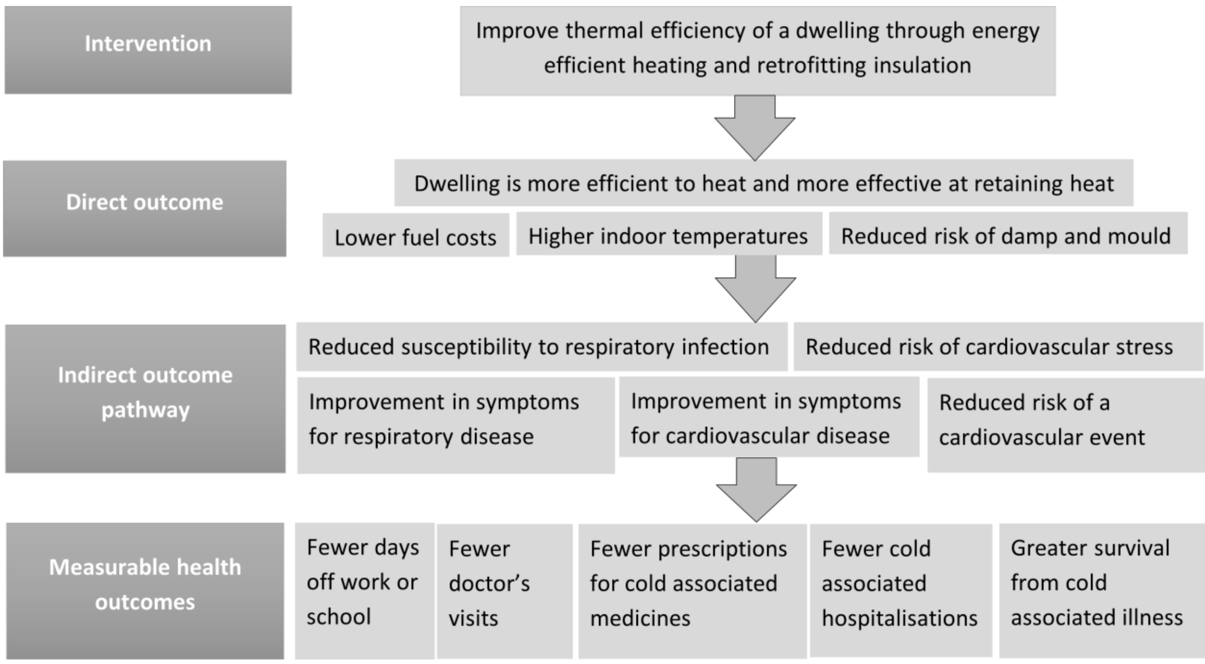
2: Evaluation Methods

2.1 Outline

New information gained for this evaluation focuses on the effectiveness of the WKH heat pump intervention in improving household energy efficiency, comfort, health, and wellbeing. The findings from this investigation of heat pump effectiveness are then combined with other information to compile CBAs relating to the WKH heat pump component, the WKH insulation component and the combined (heat pump and insulation) elements of Warmer Kiwi Homes.

Figure 2.1 provides a conceptual outline of the hypothesised causal pathways from the WKH intervention through to health outcomes. These causal pathways underpin components of the evaluation. The WKH intervention is designed to improve the thermal efficiency of a dwelling which has both direct outcomes (e.g. higher temperatures) and indirect outcomes (e.g. reduced risk of respiratory disease). These intermediate outcomes affect the health of house occupants with consequent societal (including fiscal) benefits. Separate to the health consequences, the intervention also affects resource use, including carbon emissions, via impacts on fuel consumption. The greatest gaps in our knowledge about these causal pathways regard the effects of heat pump installation on indoor temperatures, indoor dampness and energy use. These aspects therefore form key aspects of our evaluation.

Figure 2.1: Hypothesised causal pathways from WKH intervention to health outcomes



For the evaluation of heat pump effects, a before and after study design using an opportunistic sample of Warmer Kiwi Homes subsidy applicants was adopted. The study began in June 2021 in four locations across New Zealand covering each of New Zealand's three climate zones:[45] Auckland (climate zone 1), Waikato (climate zone 2), Wellington (climate zone 2) and Christchurch (climate zone 3). We group Waikato and Wellington, which are both within climate zone 2, in our analysis. Of the 2021 cohort, 85 (67%) agreed to continue in the evaluation through 2022; the remainder terminated their involvement in late 2021 as originally envisaged when the evaluation began. The continuing 2021 cohort was supplemented by a new cohort of 37 houses beginning in 2022 drawn solely from Wellington.

2.2 Study Components

The evaluation includes several components to provide a comprehensive assessment of the impacts of adding a heat pump to the living area of the home. These components comprise:

- An assessment of the physical impacts of the heat pump on temperature, relative humidity, and CO_2 levels in the living area of the house through data gathered by installation of monitoring equipment in the main living area. For the continuing 2021 cohort, this monitoring extended over two winters plus a summer (with information gathered also for spring and autumn), while for the 2022 cohort, the monitoring covered one winter.
- An assessment of occupant wellbeing and behaviours which influence energy consumption and indoor environmental quality, through data gathered via household questionnaires administered before and after heat pump installation. The questionnaires are also used to understand heating and ventilation practices and occupant reported indicators of dampness and mould. The 2021 cohort received an 'after' questionnaire in spring 2021 and those continuing in 2022 received a subsequent post-installation questionnaire in spring 2022, so responded to three surveys (including the 'before' survey.) The third survey enabled us to ask about use of the heat pump as an air conditioner over summer 2021/22. We refer to the three questionnaires henceforth as the Before, After and Subsequent surveys. The 2022 cohort received an initial Before questionnaire and an After questionnaire in spring 2022.
- An assessment of house condition through an inspection of the exterior of the house at the time of the Before survey.

- An assessment of the change in energy use of the household consequent on having the heat pump fitted by collecting smart meter electricity data from participating households. (For the 2021 cohort, we are also able to compare winter 2021 energy use of participating households with energy use from matched control households.)
- An assessment of the energy use of the heat pump by installing an energy monitoring device connected to the heat pump. This aspect of the evaluation applied only to houses in the 2022 cohort. (Analysis of the data from this aspect of the evaluation does not feed directly into the CBAs and so will be analysed in future work.)
- A set of cost-benefit analyses (CBA) for the major components of WKH at the societal level. Analysis is also conducted at the narrow fiscal level. The CBAs use the Treasury's CBAx tool to help align its results to the Treasury's Living Standards Framework (LSF).

2.3 Study Population

In designing the study, we first conducted a power calculation to determine the number of households required to provide reliable results. The power calculation used data from a 2008 New Zealand intervention study examining the effects of installing effective heating on children's health.[46] To obtain >80% statistical power, we estimated that a sample of 200 houses (acting as their own controls) would be needed to determine significant changes in respiratory symptoms and a sample of 100 houses (acting as their own controls) to determine significant changes in self-reported health.

The study population for the 2021 cohort was recruited opportunistically through five Warmer Kiwi Homes approved heat pump providers: Energy Smart, EnviroMaster, Greenside, Mint and Sustainability Trust. The study population for the 2022 cohort was recruited similarly through Sustainability Trust and Energy Smart.

2.4 Data Collection

Ethics approval for the study was obtained through the New Zealand Ethics Committee (NZEC Application 2021-16), and consultation also occurred with the Office of the Privacy Commissioner prior to data being gathered and stored. Data was collected by Motu Research and study partners: Allen & Clarke, and University of Canterbury. Advice was also received from colleagues at University of Otago, Victoria University of Wellington and Massey University. Verbal consent to collect data for the evaluation was obtained over the telephone when study participants were recruited.

Data collection was conducted by field workers based in Auckland (who also covered Waikato), Wellington, and Christchurch. Written consent, including consent to contact electricity providers for data, was collected by the field workers when they visited participating households.

2.5 Working with Heat Pump Providers

The WKH subsidy is managed via service providers who fit insulation and clean heating systems. The service providers visit applicants' homes to assess eligibility for the subsidy, and then claim the subsidy for the applicant in return for work done. In order to recruit participants who were eligible for the scheme, we worked with five of these service provision companies; two in Auckland, one each in Wellington and Christchurch, and one which operates nation-wide.

The original study design involved the service providers supplying our recruitment materials to applicants during their initial visit to assess eligibility and passing on to us the contact details for those who expressed interest in participating in the evaluation.

In 2021, difficulties in recruiting households and in accessing materials (heat pumps and monitoring equipment) were encountered as a result of supply-chain problems, related to the COVID-19 pandemic and the Suez Canal closure. These issues led to significant delays in heat pump installation. Similar delays occurred in 2022 as a result of supply chain problems (including service provider staff shortages). Consequently, in 2021 (and also for 2022), the methodology was revised so that service providers supplied us with lists of applicants who had already been approved for eligibility in order for us to make contact with the household. In these cases, we explained the nature of the study to the household after making contact. These changes led to unavoidable variability in the amount of time available to conduct baseline monitoring of the indoor environment conditions; however, we endeavoured to avoid very short baseline sampling periods (less than one week). One advantage of the variable delays in receiving a heat pump (and in some cases, not receiving a heat pump at all in the relevant monitoring period) was that the timing of heat pump installation had a large random element associated with it which gives the statistical analysis some properties of a randomised control trial in which some elements (but not all) were randomised.

In addition to helping us recruit participants into the evaluation, service providers assisted in 2022 by fitting energy monitoring devices on the heat pump during installation. The researchers acknowledge the significant contribution to our study from the five businesses who collaborated with us on this project and express our sincere thanks.

2.6 Fieldwork

Fieldworkers with experience conducting research were identified in the regions where data was being collected. In total there were six fieldworkers who undertook field work: two in each region. Fieldworkers all received training both in a seminar and by conducting their first visit with the fieldwork coordinator in order to ensure consistency of assessments.

During the initial visit to conduct the baseline survey, data was collected on the physical characteristics of the house. This included measuring the living area volume and window area and collecting data on house age, double glazing, and insulation. Floor plans of the living area were drawn for each house, including any open-plan areas which were open to the space where the heat pump was to be installed. Additionally, information was collected on foundation type, number of storeys, whether the house was detached or conjoined to others, and each house was rated on the condition of the exterior. Houses were assigned a condition rating for each of: the roof, spouting and guttering system, windows, wall claddings and, if painted, the condition of paint on exterior walls. For houses with a subfloor, information was gathered on how well the subfloor space was ventilated and whether downspouts opened to a drain, or to the ground.

2.7 The Questionnaires

Information on the demographic composition of the household, heating, ventilation and energy use habits, thermal comfort, health, and wellbeing was collected through web-based questionnaires. For the 2021 cohort, one questionnaire was scheduled to be before and one scheduled to be after the heat pump was installed.

The Before survey was completed by participants on a tablet provided by a field worker that visited the house. A second home visit was planned to conduct the 2021 follow-up survey and collect monitoring equipment. However due to the community outbreak of COVID-19 Delta variant in August 2021, the second visit became problematic so the follow-up survey was conducted over the telephone with field workers typing answers into the online survey tool. Not all participants had had their heat pump installed by the time of the second survey. A modified follow-up questionnaire was completed by the group which had did not yet had their heat pump installed.

For the 2022 cohort, we administered the Before and After surveys. The continuing 2021 cohort was sent the Subsequent survey in spring 2022, the content of which largely mirrored the After survey. One additional question referred to use of the heat pump as an air conditioner over the 2021/22 summer which has enabled us to test the impact on the outcome variables of using the heat pump as an air conditioner over summer.

2.8 Indoor Environmental Monitoring

In order to monitor the indoor environment, an EnviroQ device (supplied by Tether) was used to collect data at half-hourly intervals on temperature, relative humidity, carbon dioxide, and light. A built-in capacity for collecting sound pressure level (noise) information was disabled for this study, due to privacy issues.

In houses that did not have the network coverage required for the EnviroQ, a Hobo device was installed. Hobos are data loggers that record temperature and relative humidity also at half-hourly intervals. The Hobos need to be removed from the house in order for data to be downloaded.

In order to maximise the consistency of the monitoring data, the devices were placed using a consistent protocol which involved first asking the participant where the heat pump was to be installed, then placing the device on a perpendicular, internal wall at a distance between three and four metres from the heat pump wall. The devices were placed at 1.5m high as a compromise between measuring the lower room air space, while keeping the devices out of the way of people and furniture.

2.9 Heat Pump Electricity Flow Monitoring

For the 2022 cohort, an energy monitoring device (supplied by Efergy) was also installed. The fieldworker co-ordinated with the heat pump installer so that these devices could be fitted to the live wire of the external heat pump unit during installation of the heat pump. The Efergy monitors returned heat pump electricity use data at minute intervals, enabling precise readings both on heat pump use and electricity use. (An attempt to use different equipment for the 2021 cohort was not able to return useful information.) Detailed analysis of these data will be included in future research.

2.10 Electricity Records

Consent to collect electricity data and details of participants' electricity supply over the previous two years were collected during the first fieldwork visit. Houses were checked to determine whether they had a smart meter using the "*My Meter*" tool on the Electricity Authority's website.[47] Data from participating households who had a smart meter were requested from electricity companies through the Electricity Authority (EA) Transfer Hub. Half-hourly data were requested for up to two years prior to the date of the request.

Data supplied depended on availability from the electricity company. In some cases, companies were unable to provide any electricity consumption information for a study participant or could only provide limited records. Data quality varied between energy companies and some could not provide half-hourly breakdowns. Electricity use of participant households in each cohort acted as controls, utilising the staggered installation of heat pumps across both cohorts.

For the 2021 cohort, each individual house was also matched to up to 10 control houses that had received a heat pump in 2020. Matching was based on Stats NZ Statistical Area 2[48] and by electricity use in March 2021 (a month unaffected by summer vacations and when the heat pump was unlikely to be used for heating). The matched data enable a deeper cohort of 'control' houses against which to compare our 'treated' houses (i.e. WKH houses with a heat pump installed) than is possible when limiting the sample solely to the WKH sample houses. (We note that similar matching was not possible for the indoor environmental monitoring component as we do not have indoor monitoring results for houses beyond those in the study.)

2.11 Weather Data

Weather data were collected from the weather station closest to participating households that had a full set of records for the study. Minimum, maximum, and mean temperature were downloaded from the NIWA Cliflo website.[49] These data were used as controls for the analysis of indoor temperature, CO_2, and electricity use. Relative humidity data were also downloaded from the same weather stations to act as a control in the analysis of indoor relative humidity (and CO_2) in the living area.

3: Demographic Profile of Study Participants and House Condition at Baseline

3.1 Sample composition

The 2021 cohort comprised 127 households while the 2022 cohort comprised 37 households. Of the combined cohorts, 56 (34%) were in climate zone 1 (Auckland), 82 (50%) were in climate zone 2 (8 in Waikato and 74 in Wellington) and 26 (16%) were in climate zone 3 (Christchurch). All 164 households (across the two cohorts) completed the Before survey, 153 completed the After survey (of whom 129 had the same respondent as in the Before survey) and 85 completed the Subsequent survey (of whom 74 had the same respondent as the Before survey, and 67 had the same respondent for all three surveys).

Tables 3.1 and 3.2 detail demographic and related characteristics (across both cohorts, based on the Before surveys). The study population comprised mostly multi-person households (with an average of 2.7 people per household). The majority of participants lived in houses smaller than 100m^2, and most resided in detached single storey dwellings. Most primary respondents (and household members) were of working age (18-64 years) and most respondents were working full or part-time. Approximately half (47%) of respondents reported having “enough” or “more than enough” income to meet their needs while 7.3% had “not enough”. Over two-fifths of households (41.5%) received the Winter Energy Payment. With respect to ethnicity, the survey asked participants to indicate as many ethnicities as were applicable.

Table 3.1 reports prioritised ethnicities[50] (for clarity), showing that approximately half of respondents were NZ European or European, a quarter were of Asian ethnicity, 13.4% Māori and 8% were Pacific peoples. Recall that we have used convenience sampling (comprising applicants approved to receive a heat pump through WKH in the four sampled cities) and that applicants had to be an owner-occupier while also living in an NZDep 8-10 area, or have a Community Services Card. Each of these criteria will have affected the demographic composition of our sample, including ethnicity and age.

Table 3.1: Socio-demographic characteristics of households and respondents (Before survey)

Socio-demographic characteristic	**Number of people in household**	**Percentage of each variable**	**Number of respondents**	**Percentage of each variable**
Age				
Pre-school (<5 years)	23	5.3	0	0.0
School age (5-17 years)	62	14.2	0	0.0
Adult (18-64 years)	246	56.3	109	66.5
Older adult (≥65 years)	80	18.3	48	29.3
Did not state	26	5.9	7	4.2
Ethnicity*				
New Zealand European	173	39.6	84	51.2
Māori	73	16.7	22	13.4
Pacific peoples	65	14.8	13	8.0
Asian	120	27.5	41	25.0
Middle Eastern	2	0.5	0	0.0
Did not state	4	0.9	4	2.4
Gender				
Female	209	51.0	91	55.5
Gender neutral	5	1.1	1	0.6
Male	223	47.8	72	43.9
Labour force status				
Homemaker	14	3.2	7	4.3
Unable to work (medical)	8	1.8	2	1.2
Seeking work	14	3.2	4	2.4
Pre-schooler	23	5.3	0	0.0
Student	96	22.0	5	3.0
Working	197	45.1	94	57.3
Retired	81	18.5	47	28.7
Did not state	4	0.9	5	3.0
Region				
Auckland	151	34.6	56	34.1
Waikato	22	5.0	8	4.9
Wellington	204	46.7	74	45.1
Christchurch	60	13.7	26	15.9
Cohort				
2021	337	77.1	127	77.5
2022	100	22.9	37	22.5

Note: ** Ethnicity is prioritised.*

Table 3.2: Household characteristics of participants (Before survey)

Household characteristic	Number	Percentage of each variable
Number of people		
1	40	24.4
2	49	29.9
3	31	18.9
4	23	14.0
5	11	6.7
6	5	3.0
7	3	1.8
8+	2	1.2
Length of residence		
Less than six months	22	13.4
Six to twelve months	11	6.7
One to two years	15	9.1
More than two years	116	70.7
House size		
less than 100m^2	92	56.0
100m^2 to 200m^2	59	36.0
more than 200m^2	13	8.0
Building type		
Detached single storey	103	62.8
Detached multi storey	31	18.9
Joined	30	18.3
Sufficient income to meet needs?		
More than enough	18	11.0
Enough	59	36.0
Just enough	72	43.9
Not enough	12	7.3
Don't know	3	1.8
Received Winter Energy Payment?		
Yes	68	41.5
No	96	58.5

3.2 Health and Wellbeing

Table 3.3 indicates that self-reported health of respondents from the Before survey was mixed with 56.1% rating their health as Excellent, Very good or Good, but a further 36% rated their health as only Fair. Responses to overall life satisfaction were positive with 83.5% rating it at seven or above (on a scale of 0 to 10). When asked in the Before survey about specific areas of wellbeing (using the WHO5 questions that relate to current mental wellbeing), the response was again positive, with most providing ratings at the higher end of the scale (Table 3.4).

Table 3.3: Life satisfaction and self-reported health of respondents (Before survey)

Indicator	Number	Percentage of each variable
Life satisfaction		
0: Totally dissatisfied	0	0.0
1	0	0.0
2	1	0.6
3	2	1.2
4	3	1.8
5	8	4.9
6	11	6.7
7	46	28.0
8	41	25.0
9	23	14.0
10: Totally satisfied	27	16.5
Don't know	2	1.2
Self-reported health		
Excellent	7	4.3
Very good	24	14.6
Good	61	37.2
Fair	59	36.0
Poor	12	7.3
Don’t know	1	0.6

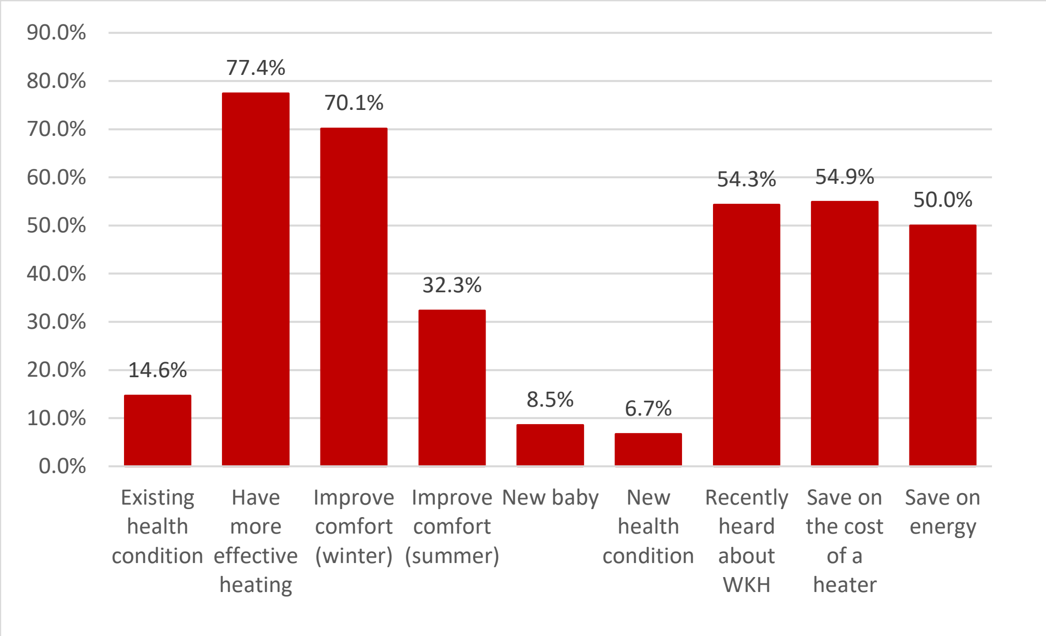
Table 3.4: WHO5 wellbeing responses based on the two weeks prior to the Before survey

Wellbeing indicator (percentage of respondents)	Always	Most of the time	More than half the time	Less than half the time	Sometimes	Never	Don't know
How often have you felt cheerful and in good spirits?	4.3	57.3	25.0	6.1	4.9	0.0	2.4
How often have you felt calm and relaxed?	4.3	42.7	35.4	11.6	4.9	0.0	1.2
How often have you felt active and vigorous?	4.3	29.3	30.5	17.1	13.4	4.3	1.2
How often have you woken up feeling fresh and rested?	3.0	32.3	26.2	20.1	14.0	3.0	1.2
How often have you felt that your daily life has been filled with things that interest you?	6.1	40.9	32.3	6.7	12.2	0.6	1.2

3.3 Motivation for Applying for the Warmer Kiwi Homes Heat Pump Subsidy Programme

When asked why they applied for a heat pump through the Warmer Kiwi Homes subsidy programme, the majority of responses centred on warmth, by either having more effective heating or improving comfort in winter (Figure 3.1). A second motivator was to save on costs, either of the heat pump itself or on energy. Improving comfort in summer - through use of the heat pump as an air conditioner - was identified by almost a third of respondents.

Figure 3.1: Reasons for applying to the Warmer Kiwi Homes subsidy programme (percent)



3.4 House Condition: Internal

Prior to heat pump installation over half the respondents (56.7%) said their house was always or often too cold in winter with just under a third reporting that they always or often limited their heating due to cost (Table 3.5).

Moisture was identified as an issue with 62.2% of households reporting that there was always or often condensation on the living room windows during winter. Householder-assessed dampness, defined as "*a damp feeling, visible damp patches or a musty or mouldy odour in the living room or any of the bedrooms*", was always or often present in winter in 20.1% of houses. Visible mould in the living area or bedroom was always or often present during winter in 14.7% of houses. Self-reported mould in these areas was lower than that reported by the BRANZ Pilot Housing Survey (PHS) 2018-19 where inspector-assessed visible mould was reported in 54% of bedrooms and 37% of living spaces.[51]

Table 3.5 Internal condition of houses (Before survey)

House condition	Number of households	Percentage of each variable
Too cold in winter		
Always	39	23.8
Often	54	32.9
Sometimes	50	30.5
Never	10	6.1
Didn't answer	11	6.7
Limited heating due to cost		
Always	30	18.1
Often	25	15.1
Sometimes	60	36.1
Rarely	13	7.8
Never	30	18.1
Don't know	8	4.8
Condensation on living room windows		
Always	58	35.4
Often	44	26.8
Sometimes	54	32.9
Never	7	4.3
Don’t know	1	0.1
House dampness		
Always	11	6.7
Often	22	13.4
Sometimes	57	34.8
Never	71	43.3
Don't know	3	1.8
Mould in living area or bedroom		
Always	6	3.7
Often	18	11.0
Sometimes	61	37.2
Never	73	44.5
Don't know	6	3.7

3.5 House Characteristics

Our sample bears strong similarities to the total sample of the Pilot Housing Survey (PHS) collected by BRANZ and Stats NZ in 2018 which included owner occupied and rental houses.[52]

The similarities are in terms of building type (62.8% detached single storey, compared to PHS 62%), window type (aluminium 60.9% vs PHS 68%), and the proportion of homes with a concrete slab foundation (32.3% vs PHS 36%). Only 17.5% of houses in the sample were never draughty, and 30.8% of participants reported that their house was often or always draughty (Table 3.6). Although our measure is not directly comparable to that used in the PHS, our sample would appear to be significantly draughtier, with the PHS reporting approximately half the sample was not draughty while 22% were “draughty or very draughty”.

As shown in Table 3.7, over half of the sample houses (57.3%) had at least one building envelope component in poor condition, while a fifth (20.1%) had three or more components in poor condition. This suggests that many houses in the sample are in a state of some disrepair. In summary, compared to the most recent, nation-wide survey of housing condition in New Zealand homes, our sample was found to be similar in terms of size and construction style to the national sample. However, it was more similar in terms of condition to rental houses and in somewhat worse condition than typical owner-occupied houses.

Table 3.6 House characteristics (Before survey)

House characteristic	Number of households	Percentage of each variable
Windows		
Aluminium	106	60.9
Timber casement	34	19.5
Timber sash	4	2.3
Mixed	30	17.2
Draughtiness		
Always	23	13.9
Often	28	16.9
Sometimes	78	47.0
Never	29	17.5
Don’t know	8	4.8
Foundations		
Slab	53	32.3
Piles	62	37.8
Perimeter wall	37	22.6
Mixed	12	7.3
Subfloor ventilation		
Sufficient	50	30.1
Insufficient	59	35.5
Slab (na)	57	34.3

Table 3.7: Building envelope condition (Before survey)

House component	**Condition (% of each component)**					
	Excellent	**Good**	**Moderate**	**Poor**	**Serious**	**Don't know**
Cladding	14.0	31.1	29.9	19.5	5.5	0
Windows	6.7	28.0	32.9	28.7	6.7	0
Paint	10.4	20.1	26.8	17.1	4.9	20.7
Roof	9.1	25.0	34.1	22.6	1.2	7.9
Gutter	7.3	33.5	32.9	19.5	4.9	1.8
Components in poor to serious condition (%)	**0 components**	**1 component**	**2 components**	**3 components**	**4 components**	**5 components**
	42.7	23.2	14.0	9.1	6.1	4.9

3.6 Heating Behaviour

Most study households (90.9%) heated their living room in winter prior to the heat pump being installed.[53] Table 3.8 shows the heating methods used (in the Before survey); a large majority of households used some form of electric heater for all rooms that were heated in winter.[54]

The heating calculator, used by the service provider to determine the size of heat pump required, measured all spaces within the living area that were not closed off by a door. The kitchen, dining room, and hallway were only counted as separate spaces from the living area in the survey if they could be shut off by a door. In some instances, these rooms were heated using the heating source from the living area by leaving doors open once the living room was warm. Those that reported using a heat pump in the living area (in the Before survey) were using a heat pump that had been installed in another part of the house and were keeping doors to the living area open. Those who listed open fires or log/ pellet burners as a means of heating hallways or bedrooms were likely to also have done so by opening doors from living areas to allow heat to spread to other parts of the house.

Table 3.8: Prior heating methods by room (Before survey)

Room	Percentage of each variable						
	Electric heater	**Flued gas heater**	**Unflued gas heater**	**Open fire**	**Log or pellet burner**	**Other**	**Not stated/no heater**
Living room	80.5	0.6	5.5	0.0	0.0	4.3	9.1
Dining room	11.6	0.6	0.6	0.0	0.6	0.0	86.6
Kitchen	6.7	0.0	0.6	0.0	0.6	0.0	92.1
Study	4.9	0.0	0.0	0.0	0.0	1.2	93.9
Hall	80.5	0.6	5.5	0.0	0.0	4.3	9.1
Master Bedroom	48.2	1.2	0.0	0.0	0.6	18	48.2

When asked about reasons for not heating rooms that were used regularly (other than cost), the most common reason was that households did not have enough heaters or that the heaters were ineffective. In addition, several responses raised concerns about the safety of leaving heaters switched on in unoccupied rooms. Very few respondents cited environmental reasons for limiting their use of heating.

3.7 Interactions between Occupants and their Houses

There was little correlation between number of occupants and house size. However, houses with a greater number of occupants were more likely to report dampness in the Before survey (Table 3.9). Each of these results is consistent with previous work.[55,56] We asked whether occupants used certain behaviours to keep warm in their homes. The most common behaviours to keep warm were to use more blankets and to wear more clothes, while some households closed off rooms or went to bed early; sleeping in the living room or sleeping in a single room were rare. The behaviours were summed and the cumulative count compared to reported draughtiness. As shown in Table 3.10, this comparison showed a clear relationship between increased draughtiness and more warming behaviours undertaken by occupants. This result, together with the prevalence of draughtiness, implies that draughtiness is a significant issue for participants in this research.

Table 3.9: House dampness by number of occupants (Before survey)

Number of occupants	**Percentage of each occupancy category**			
	Never damp	**Sometimes damp**	**Often damp**	**Always damp**
1-2 occupants	52.3	30.7	13.6	3.4
3-4 occupants	37.7	35.8	13.2	13.2
≥ 5 occupants	25.0	55.0	15.0	5.0
Total	44.1	35.4	13.7	6.8

Table 3.10: Number of warming behaviours by house draughtiness (Before survey)

Draughtiness status	**Percentage of each draughtiness status***		
	0-3 warming behaviours	4-6 warming behaviours	7-10 warming behaviours
Never draughty	48.3	41.4	10.3
Sometimes draughty	39.5	34.2	26.3
Often draughty	21.4	60.7	17.9
Always draughty	22.7	40.9	36.4

**9 responses missing*

4: Heat Pump Impacts

4.1 Surveyed impacts on Households

The 2021 cohort received three questionnaires: a (first) year Before survey in winter 2021 (prior to heat pump installation), a (first year) After survey in spring (October/November) 2021, scheduled to be after heat pump installation, and the Subsequent (second year) survey in spring (September/October) 2022. The 2022 cohort received a (first year) Before survey in winter 2022 (prior to heat pump installation), and a (first year) After survey in spring (September/October) 2022, also scheduled to be after heat pump installation. In practice, some houses in each cohort had not had their heat pump installed by the time of their After survey due to supply chain issues and, in 2021, Covid-related lockdowns. The 2021 installation delays were not evenly distributed with Wellington lagging Auckland and Christchurch.[57] Of the 117 houses (with usable survey responses) in the 2021 cohort, 100 had received their heat pump by the time of the After survey, while of the 35 houses (with usable survey responses) in the 2022 cohort, 28 had received their heat pump by the After survey. Responses to the After survey are therefore disaggregated according to whether a household had received their heat pump at the time of that survey. Houses that had yet to receive a heat pump are also included in the subsequent analysis of indoor environmental outcomes and electricity use as these houses provide a control group for houses with installed heat pumps. All 2021 cohort houses had a heat pump installed by the time of the Subsequent (second year) survey.

For the combined cohorts, we received responses to the Before survey from 166 households: 57 (34%) in Auckland, 83 (50%) in Waikato and Wellington, and 26 (16%) in Christchurch. We received responses to the After survey from 152 household. Reasons for the reduced number of respondents to the After survey included households that had withdrawn from the study. We received responses to the Subsequent survey from 85 households from the 2021 cohort. The reduced number of responses reflects households that elected not to continue in the study beyond the initial year.

When interpreting the survey results that follow, the survey timings should be borne in mind. Each of the Before surveys was conducted in winter, whereas the After and Subsequent surveys were conducted in spring. It is possible that some responses may reflect recent weather in the respondent's location with warmer weather generally being experienced in the spring surveys.

The Interim Report described the self-reported behaviours of 2021 cohort respondents in relation to use of their heat pump once installed. Approximately two-thirds switched the heat pump on when they felt cold (rather than leaving it at a set temperature or using the timer). The modal temperature set by respondents was 20^{o}C (with a reasonably symmetric distribution between 15^{o}C and 24^{o}C).

The analysis of responses to the After versus Before survey and to the Subsequent versus Before survey (for the combined cohorts) is restricted to households in which the same respondent answered both surveys. The analysis shows several positive outcomes for households in the first winter of having their heat pump fitted, as described below.

Table 4.1 shows transitions for wellbeing and related variables as reported by respondents, disaggregated according to whether they had had a heat pump fitted. The transitions show whether the respondent's wellbeing response improved, remained constant, or worsened. The broadest (evaluative) wellbeing question is the life satisfaction question used in Stats NZ's general Social Survey: "*Please think about your life as a whole these days. This includes all areas* *of your life. Where zero is completely dissatisfied, and ten is completely satisfied: How do you feel about your life as a whole?*". A further five wellbeing questions correspond to the WHO5 measure of current mental wellbeing (also used by Stats NZ) relating to cheerfulness, being calm and relaxed, being active and vigorous, feeling fresh and rested, and having daily life filled with interest. The questions are asked, for example, as: "*In the last 2 weeks, how often have you felt cheerful and in good spirits?*". In each case, response categories for the WHO5 questions comprise "*All of the time; Most of the time; More than half of the time; Less than half of the time; Some of the time; At no time; Don't know; Refused*".

In the After versus Before survey columns, the first line in each category reports transitions (worsened, constant, improved) between surveys for respondents who had had a heat pump fitted, while the second line reports transitions for those yet to receive their heat pump. Some questions in the After survey were applicable only to respondents who had received a heat pump so the 'No' row is empty for these questions.

We initially look at the transitions from the Before to the After survey. The transitions for Life satisfaction show that, of those who had received their heat pump, 47 of respondents (44%) recorded improved life satisfaction between the surveys compared with 31 (29%) whose life satisfaction had declined (the others remaining constant). For those who had yet to receive their heat pump, the responses were 7 (39%) and 5 (28%) respectively. No clear associations are apparent between heat pump installation and changes in any of the WHO5 measures or with the self-reported health measure.

A strong association is observed between heat pump installation and whether a household reported changes in their living area being cold in the previous winter. Of the households that had a heat pump fitted 85 (77%) reported a reduction in cold (i.e. an improvement) with just 8 (7%) reporting a worsening. Those without a heat pump fitted also reported a net improvement with respect to cold but the net proportion relating to an improvement was much lower than for those who had had a heat pump installed. (Our subsequent difference-in-difference estimates adjust for the experiences of households that did not receive a heat pump.) Households with a heat pump installed overwhelmingly reported improvements with respect to condensation (89% improved), dampness (47% improved) and comfort (87% improved).

Table 4.1: Wellbeing transitions with and without a heat pump installed (After versus Before, and Subsequent versus Before survey responses)

Indicator	Heat pump fitted	After vs Before			Subsequent vs Before		
		Worsened	Constant	Improved	Worsened	Constant	Improved
Life satisfaction	**Yes** **No**	31 5	30 6	47 7	20	26	27
Cheerful, good spirits	**Yes** **No**	20 2	49 11	35 5	18	33	21
Calm and relaxed	**Yes** **No**	28 5	45 5	33 8	25	25	22
Active and vigorous	**Yes** **No**	25 6	40 9	40 3	20	29	23
Fresh and rested	**Yes** **No**	34 5	31 10	41 3	20	29	23
Filled with interest	**Yes** **No**	33 3	38 9	35 6	17	18	27
Self-reported health	**Yes** **No**	21 4	61 8	27 6	11	42	21
Perceived cold	**Yes** **No**	8 4	17 5	85 9	2	13	50
Perceived condensation	**Yes** **No**	1	11	96	2	16	55
Perceived dampness	**Yes** **No**	1	56	50	1	37	35
Perceived comfort	**Yes** **No**	4	9	89	0	1	73
Restricted heating due to cost (HP)	**Yes** **No**	5	25	75	2	17	51
Restricted heating due to cost (Other)	**Yes** **No**	10	27	69	4	21	45

Notes: After vs Before shows the transition from the Before to the After Survey (covering both cohorts); Subsequent vs Before shows the transition from the Before to the Subsequent survey (covering all 2021 cohort houses with eligible responses in both surveys). In all cases, responses are limited to surveys with the same respondent in each survey. The perceived condensation, dampness, comfort and cost questions were targeted at houses that had received a heat pump by the time of the relevant survey so the 'No' category for houses without a heat pump in the After survey is empty. All houses had a heat pump installed by the Subsequent survey. The question on whether a household restricted heating due to cost in the previous winter is split into two (in the After and Subsequent surveys) covering each of restricting use of the heat pump and restricting use of other heating devices in the house.

Households with a heat pump also reported an improvement in whether they had had to restrict heating due to cost, with 71% reporting an improvement (measured as not having to restrict heat pump use due to cost relative to restricting heating due to cost in the previous winter) while 65% reported that they also had not had to restrict the use of other heaters due to cost (relative to their answer in the previous winter's survey).

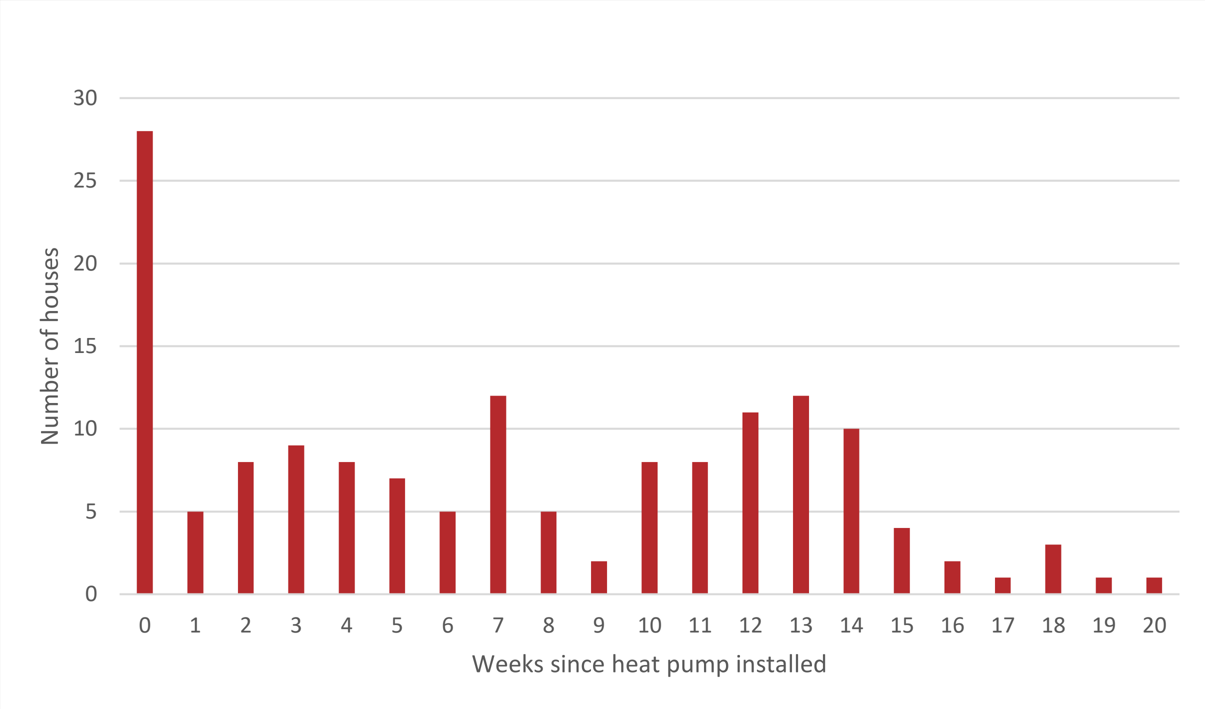
Turning to the transitions from the Before to the Subsequent surveys, we see several of the features from the first year repeated into the second year. In particular, there remains a very marked improvement in respondents' perceptions of cold, condensation and dampness, plus some indication of a net improvement in self-reported health. Households continued to be much less restricted in their use of heating because of cost, both with respect to the heat pump and other heaters in the house.

In addition to greater comfort, of those respondents who had received their heat pump, 82% said they felt more satisfied with their home at the time of the After survey with 92% feeling more satisfied with their home by the Subsequent survey;[58] 86% in the After survey (and 92% in the Subsequent survey) considered that the heat pump had met or exceeded their expectations. Furthermore, 86% of households who had a heat pump in the After surveys stated that they were very happy or happy with the Warmer Kiwi Homes subsidy programme and 93% considered that the heat pump had been the right choice for their home.

The data described above indicate that heat pump installation had positive effects on several factors that contribute to householders' wellbeing. We use the data to model the impacts that heat pump installation had on two key factors associated with the householder's wellbeing: (i) perceived cold of the house, and (ii) life satisfaction. Each question is asked of respondents in each survey whether or not the respondent had yet received their heat pump, so in each case we have a control group. However, this control group is only available for the After survey rather than for the Subsequent survey. We report descriptive statistics with respect to the Subsequent survey, but our statistical modelling, which requires a control group, is restricted to analysis of the After versus Before survey responses.

Figure 4.1 shows the number of houses in the *First winter* sample according to weeks since their heat pump had been installed at the time of the After survey. Of the 150 houses in this sample, 28 had yet to have the heat pump installed by the After survey (or had had it installed for less than one week) while the number of weeks since installation varies considerably.

Figure 4.1: Houses by number of weeks a heat pump had been installed as at After survey



Source: Data from After survey.

It is possible that wellbeing responses to the heat pump depend on length of experience with the heat pump. Accordingly, in our modelling, we adopt three different approaches to measure heat pump installation. First, we include an indicator variable (*HP_installed*) equal to 1 if a heat pump had been installed at least 1 week prior to the After survey (= 0 otherwise). Second, we disaggregate this variable according to length of experience with the heat pump by including two indicator variables (*HP_weeks_1-4* and *HP_weeks_5plus*) that are entered together as a semi-parametric specification (with zero weeks as the omitted base category); *HP_weeks_1-4* indicates that the household had a heat pump installed 1 to 4 weeks prior to the After survey and *HP_weeks_5plus* indicates that the household had a heat pump installed for at least 5 weeks at the time of the survey. Third, we include a variable (*HP_inverse_weeks*) as a parametric variable designed to proxy a smooth change in wellbeing following installation that approaches an asymptote (which indicates the long-run effect of installation). This variable is defined as:

HP_inverse_weeks = 1/(1 + number of weeks since heat pump installed, as at After survey)

HP_inverse_weeks = 1 if a heat pump is not installed and asymptotes towards 0 as the number of weeks with a heat pump increases. Reflecting a hypothesis that a heat pump positively affects wellbeing, we expect the coefficients on *HP_installed, HP_weeks_1-4* and *HP_weeks_5plus* to be positive where the dependent variable in our modelling relates to wellbeing (life satisfaction) and to be negative when the dependent variable relates to ill-being (perceived cold). Conversely, we expect the coefficient on *HP_inverse_weeks* to be negative where the dependent variable relates to wellbeing and to be positive when the dependent variable relates to ill-being (since *HP_inverse_weeks* declines as the number of weeks with a heat pump increases).

We test whether each of *HP_installed* and *HP_inverse_weeks* is associated with region and household variables that may also impact on the dependent wellbeing-related variables. (We do not separately model *HP_weeks_1-4* and *HP_weeks_5plus* as these variables mirror the influences on the other two variables.) Specifically, we test whether each of the heat pump variables is associated with the climate zone in which the house is situated (*Climate zone*), the household's perceived income situation in the Before survey (*Income meets needs*), and household occupancy numbers in the Before survey (*Occupancy*).[59] *Climate zone* relates to the city, with Auckland being climate zone 1, Waikato and Wellington being climate zone 2, and Christchurch being climate zone 3.

A logit regression for the binary *HP_installed* variable finds *Climate zone* significant ($p=0.009$) while neither *Income meets needs* nor *Occupancy* is significant at the 10% level. The ordinary least squares (OLS) regression for *HP_inverse_weeks* finds *Climate zone* significant ($p=0.014$) while again neither *Income meets needs* nor *Occupancy* is significant at the 10% level. (Robust standard errors are used in each of these regressions and throughout the paper.)

Given the association of the heat pump variables with *Climate zone*, we run each of our subsequent regressions controlling for this variable. We also include the other two variables (*Income meets needs* and *Occupancy*) in subsequent regressions since each may potentially affect wellbeing outcomes, for instance, by affecting household use of the heat pump.

Each dependent variable (*Perceived cold* and *Life satisfaction*) is an ordinal variable with more than two scale categories, so we initially model each variable using an ordered logit estimator. In each case, we have the (same) householder's responses for both the Before and After surveys for the same variable, enabling us to control for the respondent's prior response for that variable in our estimation. Consistent with the guidance of Bloem and Oswald (2022, footnote 3),[60] we include a set of indicator variables for each response category from the Before survey variable that corresponds to the dependent variable of the equation. To this equation, we add the relevant heat pump indicator (*HP_installed*, *HP_weeks_1-4* and *HP_weeks_5plus*, or *HP_inverse_weeks*) together with the control variables.

The resulting equation to be estimated is as follows for each dependent variable, where the dependent variable (*DepVar*) is one of *Perceived cold* or *Life satisfaction*), $DepVar_i^{S2}$ is the categorical response for the dependent variable in the After Survey (i.e. S2) by individual *i* where *DepVar* has *J* response categories (*1, …, J*), $DepVar_i^{S1\_j}$ is an indicator variable = 1 if individual *i* responded in that category in the (first) before survey and = 0 otherwise, $HPVar_i^{S2}$ is the relevant heat pump variable measured as at the After survey, and Z_i is a vector of control variables:

$$DepVar_i^{S2} = f\left(HPVar_i^{S2},\ \sum_{j=1}^{J} DepVar_i^{S1\_j}, Z_i\right)$$

In each case, our focus is on the estimated impact of the relevant heat pump variable on the dependent (wellbeing) variable. The equation is first estimated as an ordered logit regression and then subsequently as an OLS regression where the dependent variable is altered to become the **change** in *Perceived cold* or *Life satisfaction* from the first to the second survey (for the same respondent). To help interpret the ordered logit regression estimates, we present all coefficients in Table 4.2 as odds ratios (together with robust standard errors). Inclusion of the control variables is indicated by a 'Y' entry in the corresponding row); asterisks indicate whether the heat pump variable and each set of added control variables is statistically significant.

As hypothesised, respondents in houses that had a heat pump installed have significantly reduced odds of feeling cold in the After survey after controlling for their perceptions of cold in their house in the Before survey. This result holds for all three methods of measuring the impact of heat pump installation (i.e. columns 1-3 of the table).[61]

Columns 4-6 of Table 4.2 indicate mild support also for the hypothesis that heat pump installation raises life satisfaction (after controlling for the respondent's initial life satisfaction and for the other control variables). The effect is significant at the 10% level in column (6) which is the preferred equation according to the AIC statistic; the estimate for *HP_inverse_weeks* indicates that life satisfaction rises as length of time since installation increases.

Table 4.2: Association of perceived cold and life satisfaction with heat pump installation (odds ratios from ordered logit estimates), *First winter*

	Perceived cold			***Life satisfaction***		
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
HP_installed	0.245***			2.096		
	[0.119]			[0.972]		
HP_weeks_1-4		0.230**			1.827	
		[0.172]			[1.138]	
HP_weeks_5plus		0.248***			2.074	
		[0.123]			[0.999]	
HP_inverse_weeks			4.923***			0.401*
			[2.661]			[0.215]
Perceived cold (S1)	Y	Y	Y			
Life satisfaction (S1)				Y***	Y***	Y***
Climate zone	Y***	Y***	Y***	Y**	Y***	Y**
Income meets needs	Y	Y	Y	Y	Y	Y
Occupancy	Y	Y	Y	Y*	Y*	Y*
Observations	116	116	116	125	124	124
Pseudo-R^2	0.145	0.145	0.147	0.112	0.113	0.114
AIC	244.8	246.8	244.7	412.6	410.5	407.9

Notes: The explanatory variables, *Perceived cold, Life satisfaction, Climate zone, Income meets needs* and *Occupancy* are each from the Before survey (S1); each includes all categories of the relevant variable in the regression as indicator variables. Results are from ordered logit regressions with odds ratios reported together with robust standard errors in square parentheses. Asterisks on the control variables indicate the joint significance level of each set of variables (*** = 1%, ** = 5%, * = 10%). AIC is the Akaike information criterion (a lower value indicates a better fit relative to the number of regressors).

One issue that may affect the findings in Table 4.2 is that these questions are asked of householders who are in a subsidised programme designed to improve indoor conditions. Responses to each of these questions could therefore be primed by virtue of participating in the programme and through having answered prior survey questions relating to the heat pump. This caveat is, however, less relevant to the *HP_inverse_weeks* variable which identifies the effect off the number of weeks that a house has had a heat pump rather than from a binary variable of the house having a heat pump or not. When the binary *HP_installed* variable is added to columns (3) and (6) to test for a priming effect, it is not significant at the 10% level and the AIC in each case deteriorates.

Table 4.3 presents OLS results corresponding to the regressions in Table 4.2 but with the change in *Perceived cold* or *Life satisfaction* as the dependent variable. The assumption underlying these estimates is that the dependent variable in each case can be treated as a linear cardinal scale. This is a strong assumption although Ferrer-i-Carbonell and Frijters (2004), and subsequently many others, show that OLS regressions for life satisfaction give similar results to ordered logit regressions.[62] The OLS approach has the advantage of making interpretation of the coefficients more straightforward as the change in scale steps due to a change in the explanatory variable. The signs and significance of the results are similar across the two tables so the assumption underlying the OLS estimates appears to be a reasonable approximation.

Table 4.3: Association of changes in perceived cold and life satisfaction with heat pump installation (OLS estimates), *First winter*

	Change in *Perceived cold*			Change in *Life satisfaction*		
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
HP_installed	-0.610***			0.531		
	[0.219]			[0.369]		
HP_weeks_1-4		-0.601**			0.462	
		[0.269]			[0.432]	
HP_weeks_5plus		-0.612***			0.519	
		[0.223]			[0.382]	
HP_inverse_weeks			0.698***			-0.638
			[0.240]			[0.417]
Perceived cold (S1)	Y***	Y***	Y***			
Life satisfaction (S1)				Y***	Y***	Y***
Climate zone	Y***	Y***	Y***	Y**	Y**	Y**
Income meets needs	Y	Y	Y	Y	Y	Y
Occupancy	Y	Y	Y	Y**	Y**	Y**
Observations	116	116	116	125	124	124
R^2	0.533	0.533	0.535	0.558	0.565	0.567
AIC	295.1	297.1	294.7	436.0	433.7	431.2

Notes: The explanatory variables, *Perceived cold, Life satisfaction, Climate zone, Income meets needs* and *Occupancy* are each from the Before survey (S1); each includes all categories of the relevant variable in the regression as indicator variables. Results are from ordinary least squares (OLS) regressions with p-values based on robust standard errors in square parentheses. Asterisks on the control variables indicate the joint significance level of each set of variables (*** = 1%, ** = 5%, * = 10%). AIC is the Akaike information criterion (a lower value indicates a better fit relative to the number of regressors).

The OLS results for *Perceived cold* in Table 4.3 indicate that the impact of heat pump installation corresponds to approximately two-thirds of a step change in perception of cold (on a 4 point scale). The estimates are similar whichever heat pump measure is included in the equation and the results are in each case significant at the 1% level.

The OLS results for *Life satisfaction* are not significant at the 10% level (according to the AIC, the best equation is for *HP_inverse_weeks*, with p=0.129). While imprecise, the estimates are consistent with the ordered logit regressions and indicate that life satisfaction rises by approximately half a step (on an 11 point scale). Further investigation splits up the effect of *HP_inverse_weeks* on *Life satisfaction* by gender, finding that *Life satisfaction* increases by over a full step for males (significant at the 5% level) but that there is no significant increase for females. This result warrants further investigation.

As an additional robustness check, we have estimated two further specifications for *Life satisfaction* based on the recommendations of Bloem and Oswald (2022) in response to a criticism of Bond and Lang (2019)[63] that both ordered logit and OLS regressions with an ordinal dependent variable that has more than two steps may be subject to bias due to mis-specification (depending on the distribution of the dependent variable). Bloem and Oswald recommend forming a binary variable in which the median and above categories =1 and below median categories =0 (we call this binary variable *Life satisfaction_upper*). They also recommend forming a second binary variable in which the median and below categories =0 and above median categories =1 (we call this binary variable *Life* *satisfaction_lower*). (The median change in life satisfaction is zero, i.e. constant life satisfaction). Of the two binary variables, *Life satisfaction_lower* is more balanced across the categories (with 43% =1 and 57% =0) whereas *Life satisfaction_upper* is quite unbalanced across the categories (with 72% =1 and 28% =0); based on Bloem and Oswald, the more balanced variable (i.e. *Life satisfaction_lower*) can be expected to provide a clearer estimate. The regressions in each case show a negative coefficient for *HP_inverse_weeks* in these regressions; *Life satisfaction_upper* is not significantly different from zero, while *Life satisfaction_lower* is significant at the 10% level. These robustness tests (together with the gender result) again indicate some mild support for the hypothesis that life satisfaction rises consequent on the installation of a heat pump.

Given the wide variety of factors (especially over this period) that affected life satisfaction of respondents, the lack of precision for the *Life satisfaction* estimates is not surprising (although the results are consistent with an increase in life satisfaction). In contrast, one can expect a much more direct relationship between installation of a heat pump and perception of cold in the respondent's living area and this is what we find. Accordingly, we use the estimated effects of heat pump installation on *Perceived cold* (in conjunction with the relationship estimated by Smith and Davies between life satisfaction and *Perceived cold*, which is reflected in the Treasury's CBAx model) as a wellbeing-based input into our cost benefit analysis in this evaluation.

4.2 Indoor Environmental Quality

4.2.1 Outline

Each house in the programme received either a Tether EnviroQ or a Hobo indoor environmental monitor at the time of the Before survey. The EnviroQ monitor collected half-hourly data on indoor (living area) temperature (°C), indoor relative humidity (%RH), CO_2 (parts per million, ppm) and light (lux).

Recall that we analyse three separate seasons: *First winter*, *Second winter* and *First summer*. From a modelling perspective, restricting analysis of heating outcomes to winter months enables us to utilise the staggered installation of heat pumps over the first winter (including houses that did not receive a heat pump within the first winter).

Unlike the heating analysis, we do not have a control group of houses without a heat pump over the summer; instead, we utilise the survey response to whether the household used the heat pump as an air conditioner over *First summer* to divide the sample into a treated group and a control group. This division into treatment and control groups for air conditioning – resting on unobserved differences in households that lead to different behaviours – provides a lesser degree of exogenous differentiation between treatment and control groups than is afforded by the random timing of heat pump installation (from the perspective of the household) in the heating analyses. Similarly, we do not have a control group of houses without a heat pump for *Second winter*, so we simply compare temperature outcomes over *Second winter* with those of houses with and without a heat pump over *First winter*.

Our dataset includes monitoring data both prior to heat pump installation and post installation.[64] We draw on data from the Before household survey for variables relating to perceived draughtiness and the number of occupants of the house and draw on Cliflo weather data compiled by NIWA. The Cliflo data (for external temperature and external relative humidity) is recorded hourly at the start of each hour and is interpolated to half-hourly intervals.

Table 4.4 provides descriptive statistics for the prevalence of uncomfortable temperatures in study houses for the three periods on which we concentrate. For each of *First winter* and *Second winter*, we show the percentage of half-hourly readings that are less than 16°C and also readings that are less than 18°C. For *First winter*, we show the proportions separately for houses that have heat pumps installed and those that do not at the time of the temperature reading. In order to help control for timing of heat pump installation within the 'winter' period (when external temperature conditions could be quite different), the *First winter* readings are confined to the two weeks prior and two weeks after heat pump installation (and exclude the week of installation) for each house.

For *First summer*, we show the percentage of half-hourly readings that exceed 25°C, split by whether the household stated they used their heat pump as an air conditioner and those that did not. In each case, regional splits are shown.[65] All houses had a heat pump by *Second winter* so readings are only shown for houses with a heat pump for that season.

For the Total sample, the proportion of temperatures below each of 16°C and 18°C fell in *First winter* once a house had received a heat pump. The fall was very marked in climate zone 3 (Christchurch), less marked in climate zone 2 (Wellington and Waikato) and not observed at all in climate zone 1 (Auckland) in which the percentages increased slightly. In *Second winter*, the proportion of temperatures below each of 16°C and 18°C fell in every climate zone with the effect again being strongly observed in Christchurch. No clear results are indicated for the use of the heat pump as an air conditioner over summer, although the warmest climate zone (Auckland) does show a marked decrease in temperatures exceeding 25°C for houses that use the heat pump as an air conditioner.

These descriptive statistics do not control for external temperatures and so provide only illustrative evidence on the impacts of heat pump installation on indoor temperatures. Our subsequent modelling of heat pump impacts on *First winter and First summer* temperatures do account for external temperatures. For *Second winter*, the absence of a control group makes formal modelling of heat pump effects challenging. To gauge this second year effect, we therefore rely on the descriptive statistics in Table 4.4. These descriptive statistics provide a strong indication that any findings we observe with respect to warmer temperatures in our modelling of *First winter* are likely to be maintained, or amplified, for *Second winter*.

Table 4.4: Prevalence of uncomfortable temperatures (percent of half-hourly readings)

		Total	Auckland	Wellington and Waikato	Christchurch
		Percentage of half-hourly temperatures < 16°C			
First winter:	No heat pump	26.8	18.0	28.7	35.7
	Heat pump	22.1	20.1	24.2	19.6
Second winter:	Heat pump	18.2	11.8	24.3	19.9
		Percentage of half-hourly temperatures < 18°C			
First winter:	No heat pump	46.7	38.4	49.3	53.2
	Heat pump	41.9	40.5	45.4	33.8
Second winter:	Heat pump	37.4	32.6	46.8	29.6
		Percentage of half-hourly temperatures > 25°C			
First summer:	Heat pump not used	18.6	38.1	11.7	5.7
	Heat pump used	22.3	29.6	23.9	5.3

Note: All 2021 cohort houses had a heat pump in *Second winter*, so there is no row for 'No heat pump' in those cases. *First winter* readings are confined to the two weeks prior and two weeks after heat pump installation (and exclude the week of installation) for each house.

We model the impact of heat pump installation on each of living area temperature, relative humidity and CO_2, with most attention paid to temperature outcomes given their importance in the causal pathways from heat pump installation to health and energy use outcomes. Our modelling for *First winter* uses a 'difference-in-difference' (DiD) approach to assess the impact that installation of a heat pump has on the indoor (living area) environment.[66] We control for a number of factors including light, external temperature and humidity, and include additional indicator variables (fixed effects) that control for: (i) each house in the study (to account for unchanging features of the house such as sun and house condition, and for unchanging features of the household such as number and ages of occupants); (ii) each half-hour of the day (to account for different heating and living behaviours at particular times through the day such as sleeping and meal times); and (iii) each separate day of the study for each climate zone (*Day*CZone*] (to account for time-varying national factors and regional factors that may vary by day such as region-specific lockdowns) that affect heat pump use. Inclusion of the day fixed effects also controls for the two distinct cohorts modelled for *First Winter* (since only cohort 2021 is covered by the 2021 day fixed effects, while only cohort 2022 is covered by the 2022 day fixed effects).

We leverage the fact that heat pumps were installed on different days throughout the programme, with some 2021 cohort properties not receiving a heat pump during winter 2021, and some 2022 cohort properties not receiving a heat pump during winter 2022. The timing of heat pump installation was essentially random from the perspective of the household, being affected *inter alia* by delays related to supply chains, labour shortages and the COVID-19 pandemic (including lockdowns). Thus, we have some features of a natural experiment in which the timing of treatment can be regarded as random from the perspective of the household (though installation patterns did differ by region).

The simplest form of equation for indoor temperature that we estimate is:

$$Temp^I_{iht} = \beta_0 + \beta_1 Temp^O_{iht} + \beta_2 HP_{iht} + \mu_{tc} + \mu_h + \mu_i + \varepsilon_{iht} \qquad (1)$$

where: $Temp^I_{iht}$ is indoor (living area) temperature of house *i* at half-hour *h* on day *t*;

$Temp^O_{iht}$ is outdoor temperature at house *i*'s location at half-hour *h* on day *t*;

HP_{iht} is a dummy variable for heat pump installation (=0 pre installation; =1 post);[67]

β_0, β_1, β_2 are coefficients to be estimated;

μ_{tc} is a set of day*climate zone fixed effects to be estimated;

μ_h is a set of half-hour-of-day fixed effects to be estimated;

μ_i is a set of house fixed effects to be estimated;

ε_{iht} is the residual.

Specification (1) and subsequent specifications are estimated as an unbalanced panel equation using ordinary least squares regression; ε_{iht} will likely be correlated within each household, so standard errors are in each case clustered by house. The sample period for *First winter* covers 1 June to 30 September in the first year following application for a heat pump for each house. We estimate equation (1) on the 156 houses for which we have the required data, comprising 461,017 observations.

In specification (1), our focus is on the heat pump parameter, β_2, which indicates the average difference in indoor temperature of the house (in degrees Celsius) following heat pump installation (relative to having no heat pump installed under WKH) after controlling for external temperature.

We extend specification (1) by including the interaction effect of a heat pump with external temperature, as shown in specification (2):

$$Temp_{iht}^{I} = \beta_0 + \beta_1 Temp_{iht}^{O} + \beta_2 HP_{iht} + \beta_3 HP_{iht} Temp_{iht}^{O} + \mu_{tc} + \mu_h + \mu_i + \varepsilon_{iht} \qquad (2)$$

In specification (2), our focus is both on the heat pump parameter, β_2, and on the interaction parameter, β_3. The latter coefficient indicates whether the installation of the heat pump changed the relationship between indoor and outdoor temperature after controlling for other factors. If β_3 is significant, then the effect of a heat pump on indoor temperature (relative to external temperature) will differ according to the external temperature. At a given external temperature, having a WKH heat pump installed is estimated to raise the indoor temperature (in degrees Celsius) relative to the counterfactual of having no heat pump by: $\beta_2 + \beta_3 Temp_{iht}^{O}$. We hypothesise that $\beta_3 < 0$ so that the impact on indoor temperature of having a heat pump will increase as external temperature decreases.

The impact of the heat pump may also depend on certain house-specific factors. One of these factors for which we gather hourly data is light in the living area. The amount of light received in the room may directly affect temperature through solar gain. We can include this effect by adding a variable, *Light*, to equation (2). In further work, we tested whether the interaction of *HP* with *Light* is significant when added to the equation; the interaction term was not significant, so this extension is not reported.

Other factors that may affect the impact of the heat pump include draughtiness and number of occupants. It is likely that a heat pump will be less effective in a house that is draughty as heat will be lost from the living area. The number of occupants may have a direct effect on temperatures and may also affect behavioural use of the heat pump (e.g., a household with four occupants may feel it more worthwhile to use the heat pump than a household with a sole occupant). Data on each of these aspects is sourced from the first survey of each house. The *Draughty* variable is set equal to 0 if the house is regarded by the occupant as not being draughty and equal to 1 otherwise (i.e., if it is draughty). The *Occupants* variable is included as a set of indicator variables for the number of house occupants so that (potentially non-linear) variation in heat pump impacts across occupancy numbers can be estimated.

Each of the *Draughty* and *Occupants* variables is unchanging for each house across the sample period (since they refer to the initial survey and inspection). For this reason, we are unable to include these variables as separate explanatory variables in the specification since the house fixed effect (which is also unchanging for each house) already captures these (and all other unchanging) effects. However, we can interact *HP* with each of the *Draughty* and *Occupants* variables to test whether the impact of installing the heat pump differs according to whether a house is draughty or by the number of occupants of the house.

Extra regression results are therefore presented in which we supplement specification (2) with the addition (separately) of each of:

(a) $Light_{iht}$,
(b) $HP_{iht}Draughty_i$,
(c) $HP_{iht}Occupants_i$ (entered as a set of indicator variables).

where: $Light_{iht}$ is (living area) light in house *i* at half-hour *h* on day *t,*
$Draughty_i$ is a variable indicating if house *i* is draughty (=1) or not (=0),
$Occupants_i$ is the number of occupants in house *i*.

These equations are shown as specification (3), in which $AddedVariable$ is in each case one of the three variables (a) – (c) listed above:

$$Temp^I_{iht} = \beta_0 + \beta_1 Temp^O_{iht} + \beta_2 HP_{iht} + \beta_3 HP_{iht}Temp^O_{iht} + \beta_4 AddedVariable_{iht} + \mu_{tc} + \mu_h + \mu_i + \varepsilon_{iht} \quad (3)$$

The added variables are entered separately into specification (3) to ascertain whether any of these variables causes a change in interpretation of the estimated relationships for the effect of a heat pump.[68]

We further test whether the effect of a heat pump differs according to the time of day. We implement this approach by presenting a set of 24 separate estimates in which each equation subsets on a specific hour of the day (omitting the intervening half-hours to keep the results concise). We estimate these relationships based on specification (1), so the results show how much warmer, on average, a house is with a WKH heat pump (relative to the counterfactual) on each hour of the day.

The specifications above have been outlined with respect to internal temperature as the dependent variable. We estimate similar equations to (1) and (2) for each of relative humidity and CO_2. For relative humidity, we replace internal temperature by internal relative humidity ($Humidity^I_{iht}$) and replace outdoor temperature by outdoor relative humidity ($Humidity^O_{iht}$). This specification reflects a hypothesis that external relative humidity, rather than external temperature, is the main external determinant of internal relative humidity. We are agnostic on external determinants of CO_2, so we extend specifications (1) and (2) to include both outdoor temperature and outdoor relative humidity.

4.2.2 Indoor Temperature Results (First winter)

Table 4.5 presents estimates for the (*First winter*) indoor temperature impacts of installing a WKH heat pump using specifications (1) and (2) for the full sample.

The estimates derived from specification (1) shows that, on average, indoor (living area) temperatures rise by approximately 0.2°C for each 1°C rise in outdoor temperature (irrespective of any effect of a heat pump). After controlling for external temperature, the impact of heat pump installation is to raise indoor temperature, on average, by an estimated 1.1°C. This estimate can be taken as a summary statistic for the effect on living area temperature of installing a WKH heat pump relative to the temperature that would have existed without the installed heat pump.[69] Note that the counterfactual (i.e. the situation without the WKH heat pump) includes the effect of any prior heating devices used in the house, so the estimated impact of the heat pump on living area temperature is additional to what would previously have been experienced by the household when using its previous heating appliances.

Table 4.5: Modelling indoor temperature impacts of heat pump installation (*First winter*)

	(1)	(2)
Outdoor temperature ($Temp_{iht}^{O}$)	0.191***	0.218***
	(0.0127)	(0.0165)
Heat pump (HP_{iht})	1.101***	1.907***
	(0.237)	(0.444)
Interaction (HP_{iht}*$Temp_{iht}^{O}$)		-0.0740***
		(0.0274)
Day*CZone fixed effects	YES	YES
Half-hour fixed effects	YES	YES
House fixed effects	YES	YES
R^2	0.655	0.656
Number of houses	156	156
Observations	461,017	461,017

*Notes: Constant included but not reported. Day*CZone fixed effects are day fixed effects interacted with fixed effects for each climate zone. Standard errors (clustered on households) in parentheses; *** p<0.01, ** p<0.05, * p<0.1.*

The results of specification (2) show that, while 1.1°C is the estimated average effect across the sample, the impact differs according to outdoor temperature. If outdoor temperature were 0°C, specification (2) indicates that the heat pump is estimated to add 1.9°C to the indoor temperature (relative to the counterfactual). For each additional degree of external temperature, the heat pump contribution falls by an estimated 0.074 °C. For instance, at 11°C, which is approximately the average external temperature throughout the sample, heat pump installation is estimated to raise indoor temperature by about 1.1°C (≈ 1.907 - 0.074*11). In each case, these increases are relative to the counterfactual of not installing a WKH heat pump.

Figure 4.2 depicts the estimated living area temperatures versus outdoor temperatures ranging from 0°C to 20°C for a house with a WKH heat pump installed (HP=1) relative to the same house without the heat pump (HP=0). In each case, the 95% confidence interval (CI) is shown. To interpret the graph, take the case of an external temperature of 5°C. In that case, the internal temperature is estimated almost to reach the WHO recommended indoor minimum temperature of 18°C with a heat pump, whereas without a heat pump the indoor temperature would only be 16.4°C. In a house without a heat pump, the internal temperature is estimated to reach 18°C only once external temperature reaches approximately 12.5°C. The figure shows that the difference in internal temperatures with a WKH heat pump relative to without a WKH heat pump is statistically significant except at the very top end of the external temperature range where the confidence intervals overlap (i.e., at 20°C).

Figure 4.2: Modelled temperature with and without a WKH heat pump (*First winter*)

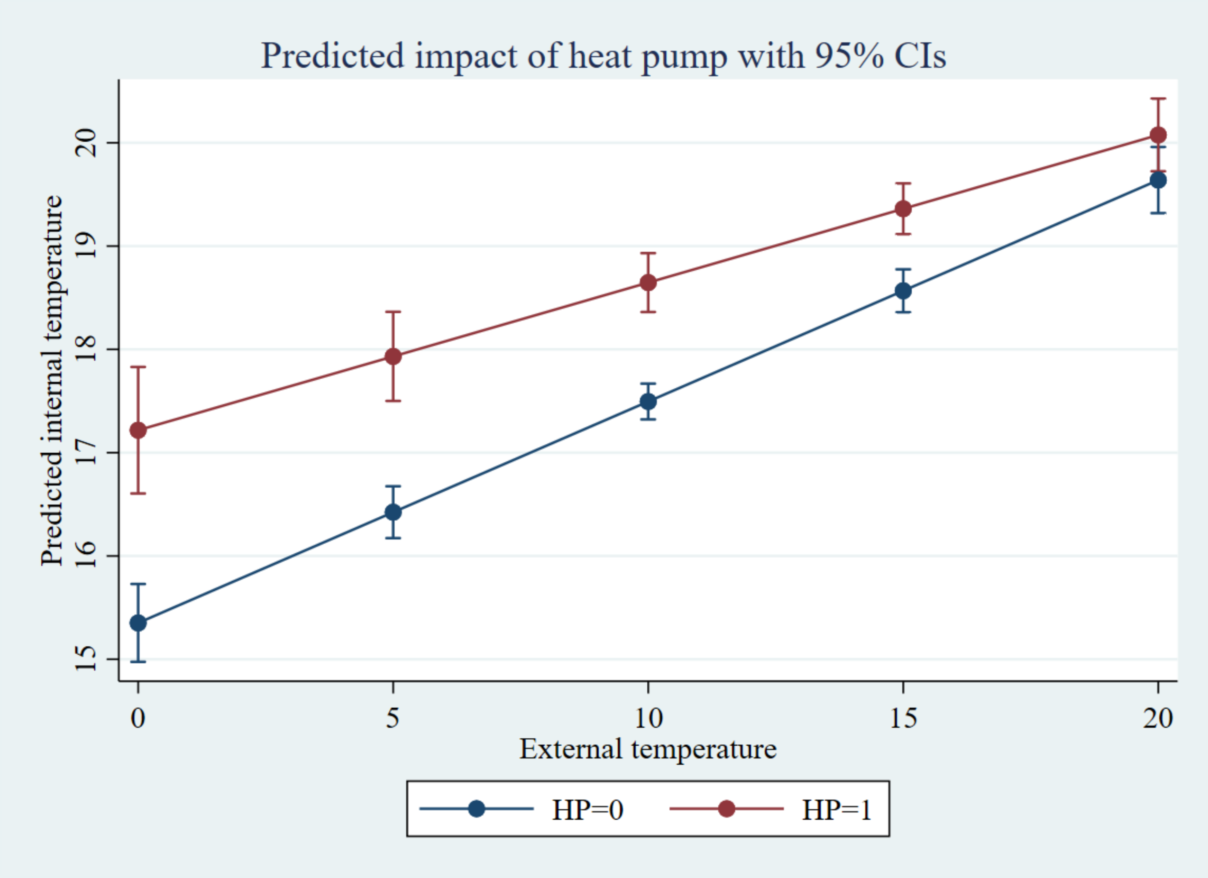


Table 4.6 presents results in which we estimate specification (3) to test for additional effects from each of light, draughtiness and number of occupants. These extensions provide us with robustness checks on the magnitudes of the estimated responses from specification (2) once we control for other potential influences on indoor temperature and heat pump use. As shown in the table, estimates of the heat pump's impact on indoor temperatures remain consistently strong in the presence of these added influences. Nevertheless, several results are of interest.

First, as hypothesised, a living area which receives greater light has a higher temperature than one that receives less light, after controlling for outdoor temperatures and the presence of a heat pump.

Second, a heat pump is less effective in raising the indoor temperature when a house is perceived as draughty; indeed, the estimated impact of the heat pump – evaluated at the mean outdoor temperature – on indoor temperature reduces from an average of 2.1°C for a non-draughty house to 0.9°C for a draughty house.

Third, heat pump effects are estimated to vary according to occupancy. The estimates (which are not reported individually in the table) indicate that (relative to a single person household) heat pump installation is associated with an extra 2.7°C increase in living area temperature for a household with 5 occupants (which is most likely a family with children).

Table 4.6: Extended modelling of indoor temperature impacts (*First winter*)

	(3a)	(3b)	(3d)
Outdoor temperature ($Temp^{O}_{iht}$)	0.209***	0.218***	0.220***
	(0.0158)	(0.0166)	(0.0165)
Heat pump (HP_{iht})	1.896***	2.876***	1.566***
	(0.441)	(0.733)	(0.542)
Interaction (HP_{iht}*$Temp^{O}_{iht}$)	-0.0736***	-0.0742***	-0.0759***
	(0.0272)	(0.0269)	(0.0271)
Light ($Light_{iht}$)	0.300***		
	(0.0432)		
Draughtiness ($Draughty_i$)		-1.153*	
		(0.603)	
Occupants (indicator variables)	NO	NO	YES
Day*CZone fixed effects	YES	YES	YES
Half-hour fixed effects	YES	YES	YES
House fixed effects	YES	YES	YES
R^2	0.660	0.658	0.659
Number of houses	156	156	156
Observations	461,017	448,919	461,017

*Notes: Constant included but not reported. Day*CZone fixed effects are day fixed effects interacted with fixed effects for each climate zone. Standard errors (clustered on households) in parentheses; *** p<0.01, ** p<0.05, * p<0.1.*

Tables 4.7 to 4.10 present hour-specific estimates for specification (1) excluding the half-hour-of-day fixed effects which are redundant given that each regression subsets on a single hour of the day. Each table shows results for six separate hourly regressions; for instance, Table 4.7 presents results for midnight through to 5 a.m., while Table 4.10 has results for 6 p.m. through to 11 p.m. The results show that there is a statistically significant increase in temperature as a result of the installed heat pump for each hour of the day.

Table 4.7: Indoor temperature impacts, Midnight – 5.00 a.m. (First winter)

	0 a.m.	1 a.m.	2 a.m.	3 a.m.	4 a.m.	5 a.m.
Outdoor temperature ($Temp^{O}_{iht}$)	0.0763***	0.116***	0.127***	0.136***	0.135***	0.143***
	(0.0214)	(0.0204)	(0.0206)	(0.0201)	(0.0214)	(0.0206)
Heat pump (HP_{iht})	0.964***	0.870***	0.804***	0.832***	0.848***	0.907***
	(0.279)	(0.256)	(0.243)	(0.250)	(0.250)	(0.257)
Day*CZone fixed effects	YES	YES	YES	YES	YES	YES
Half-hour fixed effects	NO	NO	NO	NO	NO	NO
House fixed effects	YES	YES	YES	YES	YES	YES
R^2	0.689	0.722	0.739	0.747	0.749	0.743
Number of houses	156	156	156	156	156	156
Observations	9,460	9,561	9,553	9,555	9,561	9,565

*Notes: Constant included but not reported. Day*CZone fixed effects are day fixed effects interacted with fixed effects for each climate zone. Standard errors (clustered on households) in parentheses; *** p<0.01, ** p<0.05, * p<0.1.*

Table 4.8: Indoor temperature impacts, 6.00 a.m. – 11.00 a.m. (First winter)

	6 a.m.	7 a.m.	8 a.m.	9 a.m.	10 a.m.	11 a.m.
Outdoor temperature ($Temp^{O}_{iht}$)	0.157***	0.172***	0.191***	0.232***	0.250***	0.230***
	(0.0205)	(0.0220)	(0.0240)	(0.0331)	(0.0463)	(0.0510)
Heat pump (HP_{iht})	1.026***	1.241***	1.474***	1.573***	1.547***	1.466***
	(0.269)	(0.305)	(0.331)	(0.326)	(0.310)	(0.286)
Day*CZone fixed effects	YES	YES	YES	YES	YES	YES
Half-hour fixed effects	NO	NO	NO	NO	NO	NO
House fixed effects	YES	YES	YES	YES	YES	YES
R^2	0.737	0.724	0.719	0.709	0.694	0.676
Number of houses	156	156	156	156	156	156
Observations	9,570	9,579	9,559	9,577	9,579	9,591

*Notes: Constant included but not reported. Day*CZone fixed effects are day fixed effects interacted with fixed effects for each climate zone. Standard errors (clustered on households) in parentheses; *** p<0.01, ** p<0.05, * p<0.1.*

Table 4.9: Indoor temperature impacts, Midday – 5.00 p.m. (First winter)

	12 p.m.	1 p.m.	2 p.m.	3 p.m.	4 p.m.	5 p.m.
Outdoor temperature ($Temp^{O}_{iht}$)	0.222***	0.232***	0.221***	0.258***	0.303***	0.284***
	(0.0539)	(0.0504)	(0.0507)	(0.0523)	(0.0556)	(0.0497)
Heat pump (HP_{iht})	1.313***	1.112***	0.991***	0.939***	0.898***	0.988***
	(0.261)	(0.234)	(0.217)	(0.206)	(0.197)	(0.224)
Day*CZone fixed effects	YES	YES	YES	YES	YES	YES
Half-hour fixed effects	NO	NO	NO	NO	NO	NO
House fixed effects	YES	YES	YES	YES	YES	YES
R^2	0.664	0.660	0.662	0.667	0.670	0.668
Number of houses	156	156	156	156	156	156
Observations	9,596	9,617	9,630	9,648	9,669	9,650

*Notes: Constant included but not reported. Day*CZone fixed effects are day fixed effects interacted with fixed effects for each climate zone. Standard errors (clustered on households) in parentheses; *** p<0.01, ** p<0.05, * p<0.1.*

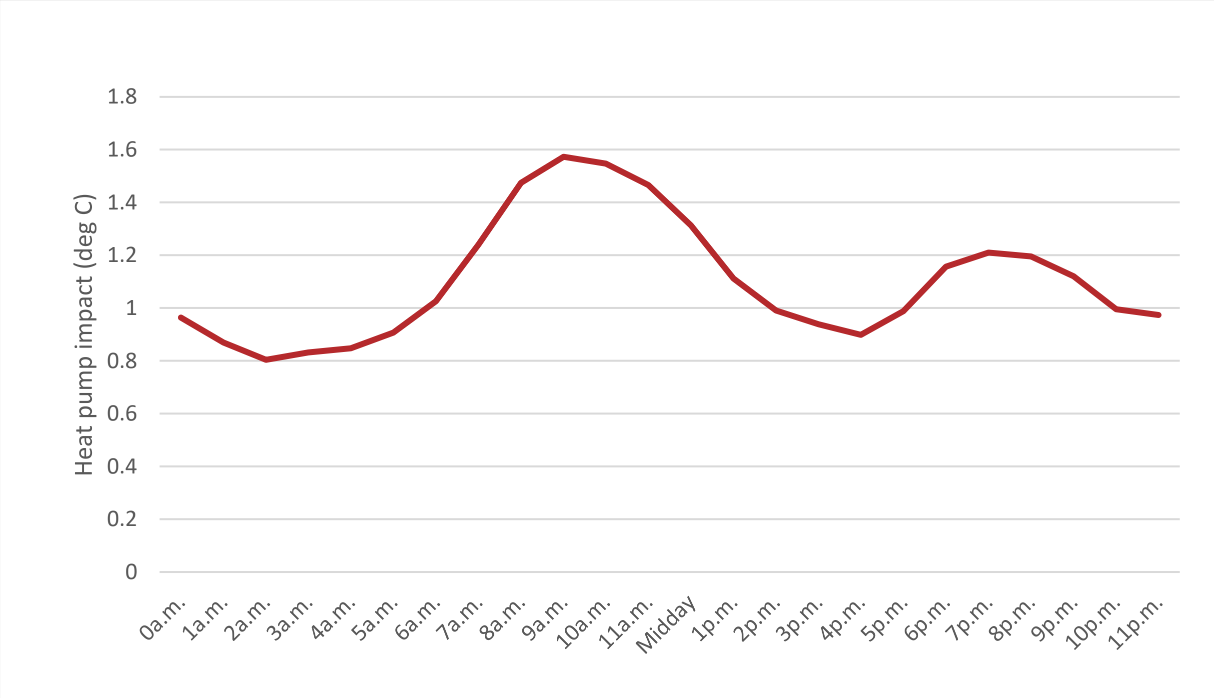
Table 4.10: Indoor temperature impacts, 6.00 p.m. – 11.00 p.m. (First winter)

	6 p.m.	7 p.m.	8 p.m.	9 p.m.	10 p.m.	11 p.m.
Outdoor temperature ($Temp^{O}_{iht}$)	0.185***	0.0779*	0.0522*	0.0742**	0.0797***	0.0795***
	(0.0565)	(0.0412)	(0.0311)	(0.0295)	(0.0273)	(0.0232)
Heat pump (HP_{iht})	1.157***	1.210***	1.195***	1.121***	0.996***	0.974***
	(0.270)	(0.296)	(0.306)	(0.311)	(0.309)	(0.297)
Day*CZone fixed effects	YES	YES	YES	YES	YES	YES
Half-hour fixed effects	NO	NO	NO	NO	NO	NO
House fixed effects	YES	YES	YES	YES	YES	YES
R^2	0.662	0.656	0.649	0.651	0.651	0.673
Number of houses	156	156	156	156	156	156
Observations	9,659	9,679	9,669	9,663	9,658	9,605

*Notes: Constant included but not reported. Day*CZone fixed effects are day fixed effects interacted with fixed effects for each climate zone. Standard errors (clustered on households) in parentheses; *** p<0.01, ** p<0.05, * p<0.1.*

These average hourly effects of heat pump installation on indoor temperature are summarised in Figure 4.3. The figure demonstrates that while the increased temperatures (relative to the counterfactual) occur throughout the day, they are most prominent around the morning breakfast period and the evening dinner period with the latter lingering through the evening.

Figure 4.3: Average temperature impact of heat pump by hour of day (*First winter*)



4.2.3 Indoor Relative Humidity and CO_2 Results (First winter)

Table 4.11 presents results from estimating specifications (1) and (2) for living area relative humidity and CO_2 respectively. The relative humidity specification includes outdoor relative humidity in place of outdoor temperature as an explanatory variable while the CO_2 specification includes both outdoor temperature and outdoor relative humidity.

The results in the first two columns show that indoor relative humidity is, as hypothesised, positively related to external relative humidity. Controlling for this effect, installation of a heat pump significantly reduces relative humidity in the living area by an amount that is equal to approximately 5% of the average level of indoor relative humidity across the sample (and equal to almost 30% of the sample standard deviation). Thus a heat pump installed through WKH not only increases the temperature but also materially reduces dampness in the living area. The interaction term shows that this reduction in living area relative humidity is greater when external humidity is high.

The last column of Table 4.11 indicates that indoor CO_2 is positively related to external relative humidity and negatively related to external temperature. Heat pump installation is associated with a reduction in living area CO_2, especially at low temperatures. While we do not have strong theoretical priors on the impacts of external temperature and relative humidity on the efficacy of the heat pump with respect to CO_2, one potential explanation for these results is that household members may be more likely to leave the living area door open when a heat pump is operating than otherwise. (There is some evidence of these behaviours in the responses to the household After survey.) The greater airflow can then act to reduce CO_2 in the room.

Table 4.11: Modelling indoor CO_2 impacts of heat pump installation (First winter)

	Relative humidity		**CO_2**	
	(1)	(2)	(1)	(2)
Outdoor temperature ($Temp^O_{iht}$)			-5.964***	-8.166***
			(2.280)	(2.972)
Outdoor humidity ($Humidity^O_{iht}$)	0.0913***	0.107***	2.376***	2.344***
	(0.00933)	(0.0122)	(0.330)	(0.471)
Heat pump (HP_{iht})	-3.340***	-0.401	-40.43	-131.8*
	(0.679)	(1.473)	(24.50)	(73.22)
Interaction (HP_{iht}*$Temp^O_{iht}$)				6.473*
				(3.519)
Interaction (HP_{iht}*$Humidity^O_{iht}$)		-0.0368**		0.261
		(0.0182)		(0.590)
Day*CZone fixed effects	YES	YES	YES	YES
Half-hour fixed effects	YES	YES	YES	YES
House fixed effects	YES	YES	YES	YES
R^2	0.728	0.728	0.847	0.847
Number of houses	156	156	156	156
Observations	461,006	461,006	458,823	458,823

*Notes: Constant included but not reported. Day*CZone fixed effects are day fixed effects interacted with fixed effects for each climate zone. Standard errors (clustered on households) in parentheses; *** p<0.01, ** p<0.05, * p<0.1.*

4.2.5 First summer

We model the impact of using the heat pump as an air conditioner over summer where the 2021 cohort is split according to whether the respondent to the Subsequent survey answered that they had used the heat pump as an air conditioner over the 2021/22 summer. All respondents had received their heat pump by February 2022 (the start of our *First summer* period) so we cannot add a term for having a heat pump (air conditioner) by itself but we can interact a term for use of the heat pump as an air conditioner ($AirCon_{iht}$) with outdoor temperature to test if these houses experienced lower indoor temperatures conditional on the outdoor temperature. Hence, we estimate:

$$Temp^{I}_{iht} = \beta_0 + \beta_1 Temp^{O}_{iht} + \beta_2 AirCon_{iht} Temp^{O}_{iht} + \mu_{tc} + \mu_h + \mu_i + \varepsilon_{iht} \quad (4)$$

The estimates (covering 200,892 observations for 121 houses) indicate that indoor temperatures are lower, on average throughout the day, by approximately 0.5°C for every extra 10°C in outdoor temperature. This coefficient is imprecisely estimated (p=0.122) possibly because the air conditioning is used only during certain parts of the day resulting in considerable variation in the temperature reduction across the sample.

To investigate this hypothesis further, in Tables 4.12-4.15 we present regressions estimated for each hour for the same specification. Use of a heat pump as an air conditioner results in significant temperature reductions (relative to houses that do not use the appliance as an air conditioner) from late morning through to the evening.

Figure 4.4 presents the information from tables 4.12 to 4.15 by hour of day where the scale corresponds to the living area temperature reduction (°C) for a house that uses the heat pump as an air conditioner for a 10°C increase in outdoor temperature. The greatest temperature reduction (relative to a house that does not use the heat pump as an air conditioner) is experienced in the afternoon with the effect lingering through to late evening. We expect that these estimated temperature reductions will be under-estimates of the temperature impacts when using air conditioning since the estimates cannot account for the exact times when the heat pump was actually used as an air conditioner; hence the estimates reflect average effects across times when the heat pump was used and was not used for air conditioning.

Table 4.12: Indoor temperature impacts, Midnight – 5.00 a.m. (*First summer*)

	0 a.m.	1 a.m.	2 a.m.	3 a.m.	4 a.m.	5 a.m.
Outdoor temperature ($Temp^{O}_{iht}$)	0.231***	0.216***	0.209***	0.212***	0.211***	0.227***
	(0.0312)	(0.0287)	(0.0285)	(0.0278)	(0.0299)	(0.0309)
AirCon*Outdoor temperature	-0.0518*	-0.0446*	-0.0426*	-0.0364	-0.0324	-0.0266
	(0.0265)	(0.0246)	(0.0240)	(0.0238)	(0.0239)	(0.0234)
Day*CZone fixed effects	YES	YES	YES	YES	YES	YES
Half-hour fixed effects	NO	NO	NO	NO	NO	NO
House fixed effects	YES	YES	YES	YES	YES	YES
R^2	0.825	0.843	0.853	0.862	0.869	0.872
Number of houses	121	121	121	121	121	121
Observations	4,178	4,189	4,189	4,189	4,189	4,189

*Notes: Constant included but not reported. Day*CZone fixed effects are day fixed effects interacted with fixed effects for each climate zone. Standard errors (clustered on households) in parentheses; *** p<0.01, ** p<0.05, * p<0.1.*

Table 4.13: Indoor temperature impacts, 6.00 a.m. – 11.00 a.m. (*First summer*)

	6 a.m.	7 a.m.	8 a.m.	9 a.m.	10 a.m.	11 a.m.
Outdoor temperature ($Temp^{O}_{iht}$)	0.232***	0.231***	0.301***	0.382***	0.415***	0.402***
	(0.0318)	(0.0306)	(0.0358)	(0.0446)	(0.0493)	(0.0544)
AirCon*Outdoor temperature	-0.0246	-0.0150	-0.0160	-0.0382	-0.0648*	-0.0814**
	(0.0237)	(0.0251)	(0.0309)	(0.0360)	(0.0380)	(0.0406)
Day*CZone fixed effects	YES	YES	YES	YES	YES	YES
Half-hour fixed effects	NO	NO	NO	NO	NO	NO
House fixed effects	YES	YES	YES	YES	YES	YES
R^2	0.867	0.856	0.840	0.836	0.812	0.802
Number of houses	121	121	121	121	121	121
Observations	4,189	4,189	4,189	4,189	4,187	4,189

*Notes: Constant included but not reported. Day*CZone fixed effects are day fixed effects interacted with fixed effects for each climate zone. Standard errors (clustered on households) in parentheses; *** p<0.01, ** p<0.05, * p<0.1.*

Table 4.14: Indoor temperature impacts, Midday – 5.00 p.m. (*First summer*)

	12 p.m.	1 p.m.	2 p.m.	3 p.m.	4 p.m.	5 p.m.
Outdoor temperature ($Temp^{O}_{iht}$)	0.377***	0.362***	0.388***	0.404***	0.433***	0.461***
	(0.0559)	(0.0513)	(0.0477)	(0.0466)	(0.0446)	(0.0420)
AirCon*Outdoor temperature	-0.0774*	-0.0738*	-0.0720	-0.0829*	-0.102*	-0.120**
	(0.0416)	(0.0442)	(0.0465)	(0.0485)	(0.0516)	(0.0508)
Day*CZone fixed effects	YES	YES	YES	YES	YES	YES
Half-hour fixed effects	NO	NO	NO	NO	NO	NO
House fixed effects	YES	YES	YES	YES	YES	YES
R^2	0.799	0.795	0.791	0.778	0.760	0.742
Number of houses	121	121	121	121	121	121
Observations	4,178	4,178	4,178	4,178	4,178	4,178

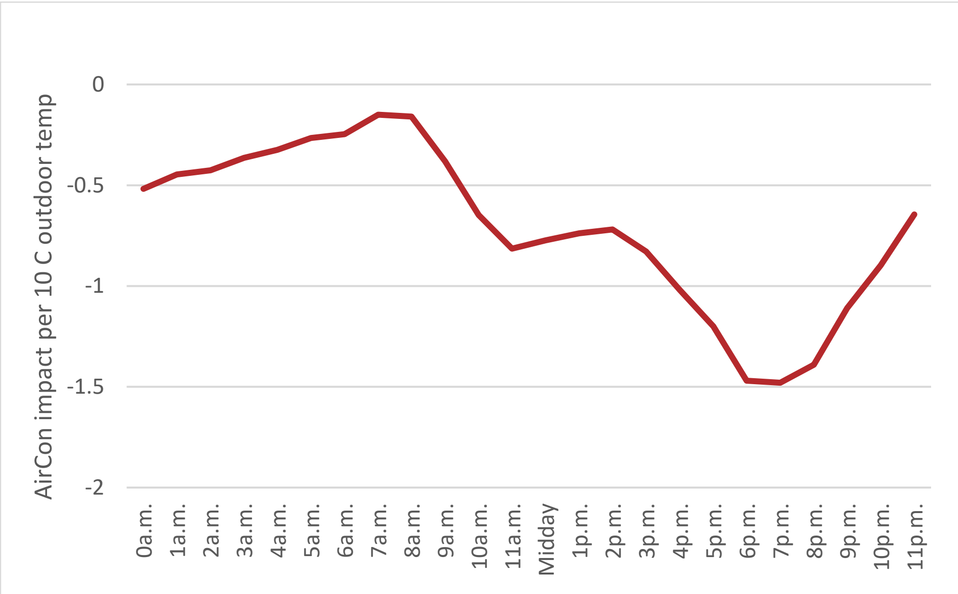
*Notes: Constant included but not reported. Day*CZone fixed effects are day fixed effects interacted with fixed effects for each climate zone. Standard errors (clustered on households) in parentheses; *** p<0.01, ** p<0.05, * p<0.1.*

Table 4.15: Indoor temperature impacts, 6.00 p.m. – 11.00 p.m. (*First summer*)

	6 p.m.	7 p.m.	8 p.m.	9 p.m.	10 p.m.	11 p.m.
Outdoor temperature ($Temp^{O}_{iht}$)	0.490***	0.506***	0.478***	0.354***	0.283***	0.250***
	(0.0417)	(0.0474)	(0.0491)	(0.0543)	(0.0489)	(0.0371)
AirCon*Outdoor temperature	-0.147***	-0.148***	-0.139***	-0.111***	-0.0897**	-0.0645**
	(0.0506)	(0.0477)	(0.0408)	(0.0406)	(0.0364)	(0.0301)
Day*CZone fixed effects	YES	YES	YES	YES	YES	YES
Half-hour fixed effects	NO	NO	NO	NO	NO	NO
House fixed effects	YES	YES	YES	YES	YES	YES
R^2	0.723	0.722	0.737	0.732	0.759	0.798
Number of houses	121	121	121	121	121	121
Observations	4,189	4,189	4,189	4,189	4,189	4,178

*Notes: Constant included but not reported. Day*CZone fixed effects are day fixed effects interacted with fixed effects for each climate zone. Standard errors (clustered on households) in parentheses; *** p<0.01, ** p<0.05, * p<0.1.*

Figure 4.4: Average temperature impact (°C) of air conditioner use per 10°C increase in outdoor temperature by hour of day (*First summer*)



4.2.6 Second winter

We do not formally model outcomes of having the heat pump in Second winter given the lack of control houses without a heat pump for this season. Recall, however, the descriptive statistics presented in Table 4.4 which showed the marked reduction of cold temperatures in houses during *Second winter* relative both to houses without and with a heat pump in *First winter*. These descriptive statistics indicate that the heat gains experienced during *First winter* were maintained, or even amplified, in *Second winter*.

4.2.7 Summary of Indoor Environmental Impacts

The design of the evaluation, in conjunction with the (unintended) randomisation of heat pump installation across houses, has enabled clear results to emerge regarding the impacts of WKH heat pump installation on indoor environmental outcomes. For *First winter*, relative to the counterfactual of having no heat pump in the living area, installation of a WKH heat pump is estimated to increase living area temperature by 1.1°C on average across the day. Gains in heat are more pronounced when outdoor temperatures are low; time of day is also a factor, with greater increases in average temperature in the morning and evening periods when homes are more likely to be occupied.

One important finding is that the efficacy of the heat pump on temperature is curtailed when a house is draughty. Draught-stopping within houses may therefore be an important complement to heat pump installation. In addition, we find that installation of a heat pump reduces relative humidity in the living area, so the overall effect of heat pump installation is to have a warmer, drier living area in a treated house. CO_2 in the living area is also reduced following heat pump installation. The *Second winter* descriptive statistics indicate that the temperature gains continue beyond the first year; hence we also expect that the reductions in relative humidity and CO_2 in the living area are subsequently maintained.

The *First summer* effects for houses that use the heat pump as an air conditioner (relative to those houses that don't use it for this purpose) show a significant reduction in house temperatures with the effect rising through the afternoon and peaking in early evening (after controlling for outdoor temperature).

These indoor environmental outcomes of heat pump installation are important for the cost benefit analysis that follows. Estimates of heat pump benefits in that analysis rely on estimated savings calculated in other studies from improvements in health consequent on installation of a heat pump. The results produced here (in conjunction with the survey results) provide strong evidence that a causal pathway exists from installing a heat pump in the living area through to temperature, relative humidity and CO_2 outcomes that are likely to lead to improved health and wellbeing.

4.3 Electricity Use

4.3.1 Outline

A housing retrofit such as installation of a heat pump may result in either a rise or a fall in a household's electricity use depending on prior heating options, the relative efficiency of the heat pump and the use of the heat pump by the household.[70] We model how installation of a heat pump in WKH houses affects household electricity use in each of *First winter* and *First summer*. (As before, the lack of a control group for *Second winter* precludes analysis of this period.) Our electricity dataset comprises half-hourly electricity consumption data collected from individual energy providers through the Electricity Authority transfer hub.

The modelling is conducted using two separate approaches. The first approach uses the same difference-in-difference approach as used for the indoor environmental modelling together with controls for the presence (and type) of living room heating used by the household prior to the heat pump being fitted. The second approach adds a matched control group of houses drawn from WKH houses previously fitted with a heat pump against which the newly treated houses (i.e. the houses in our study) are compared. The two approaches give almost identical estimates of electricity savings so we present only the first approach that is confined to our WKH sample so as to be consistent with the indoor environmental modelling results. (The finding that the two approaches give almost identical results provides assurance that the indoor environmental results, which rely solely on our WKH sample in the absence of a separate control group, provide reliable estimates for the temperature, humidity and CO_2 impacts of heat pump installation.)

4.3.2 First winter

We adopt specifications based on those used to model the indoor environmental outcomes. We hypothesise that over and above the impacts of Day*CZone, half-hour-of-day and house fixed effects, electricity use will reflect the outdoor temperature for the house. This hypothesis reflects prior findings that a substantial portion of household electricity use is attributed to space heating, especially in winter months.[71] Consistent with the previous analysis, we estimate specifications (5) and (6) in which electricity use in each half-hour is the dependent variable:

$$Electricity_{iht} = \beta_0 + \beta_1 Temp^O_{iht} + \beta_2 HP_{iht} + \mu_{tc} + \mu_h + \mu_i + \varepsilon_{iht} \quad (5)$$

$$Electricity_{iht} = \beta_0 + \beta_1 Temp^O_{iht} + \beta_2 HP_{iht} + \beta_3 HP_{iht} Temp^O_{iht} + \mu_{tc} + \mu_h + \mu_i + \varepsilon_{iht} \quad (6)$$

where: $Electricity_{iht}$ is electricity use (measured as kilowatts, kW) of house *i* during half-hour *h* on day *t*; and other variables are as described earlier.

To test whether effects differ according to prior heating type, we also estimated an extension of (6) as follows:

$$Electricity_{iht} = \beta_0 + \beta_1 Temp^O_{iht} + \beta_2 HP_{iht} + \beta_3 HP_{iht} Temp^O_{iht} + \sum_{j=1}^{3} \gamma_j A_{ij} HP_{iht} + \sum_{j=1}^{3} \delta_j A_{ij} HP_{iht} Temp^O_{iht} + \mu_{tc} + \mu_h + \mu_i + \varepsilon_{iht} \quad (7)$$

where: A_{i1} is an indicator variable for whether household *i* previously heated the living room with an electric heating appliance (of any type), A_{i2} =1 is an indicator variable for whether household *i* previously heated the living room with a gas heating appliance, A_{i3} =1 is an indicator variable for whether household *i* previously heated the living room with any other form of heating appliance (including open fire), and where no previous heating is the omitted base category. None of the interaction terms involving prior heating source was significant at the 5% level so we do not report these results. In addition, we have tested other extensions of specification (6) to include the additional variables that were added to the temperature equation, but again none of the additional variables was significant at the 5% level so these results are not presented.

In addition to estimating specifications (5) and (6), we estimate specification (5) for each hour as in the previous temperature estimates. Table 4.16 presents the estimates from specifications (5) and (6) while Tables 4.17 to 4.20 present the hourly results for specification (5).

The estimates in Table 4.16 results show that, as hypothesised, electricity use rises as external temperatures fall. The estimates for specification (5) indicate that heat pump installation, on average, reduces electricity use by approximately 16% through the winter period (= -0.0720 / 0.4515, where 0.4515 kWh is the average electricity use per half-hour).[72] The estimates in specification (6) indicate that while outdoor temperature influences electricity use, the impact of the heat pump on electricity use is not temperature dependent (i.e. the interaction term is not significant). We note that the relationship between electricity use, outdoor temperature and heat pump installation is modelled only over the winter period, so applies to a cold season; we cannot extrapolate the estimates to warmer outdoor temperatures.[73]

Table 4.16: Electricity use impacts of heat pump installation (*First winter*)

	(5)	(6)
Outdoor temperature ($Temp^O_{iht}$)	-0.0119***	-0.0116***
	(0.00242)	(0.00256)
Heat pump (HP_{iht})	-0.0720**	-0.0491
	(0.0348)	(0.0481)
HP_{iht}*$Temp^O_{iht}$		-0.00211
		(0.00330)
Day*CZone fixed effects	YES	YES
Half-hour fixed effects	YES	YES
House fixed effects	YES	YES
R^2	0.471	0.471
Number of houses	121	121
Observations	412,194	412,194

*Notes: Constant included but not reported. Standard errors (clustered on households) in parentheses; *** p<0.01, ** p<0.05, * p<0.1. Mean of dependent variable is 0.4515 KwH (measured over a half-hour period).*

The separate hour-of-day estimates for electricity use presented in Tables 4.17 to 4.20, based on specification (5), are summarised in Figure 4.5. The estimates show negligible change in electricity use through the night after heat pump installation but then show consistent electricity savings from 8am through to 9 pm. The savings reach a peak, both in terms of magnitude and statistical significance between 5pm and 9pm despite temperature gains also being experienced at this time. This result is likely to reflect households previously heating their living area in the evening using less efficient heating appliances prior to the heat pump being fitted. Alongside the statistical significance of the electricity results (especially for the late afternoon and evening), the pattern of reductions in electricity consumption provides a strong measure of reassurance that the results reflect genuine savings in electricity use as a result of heat pump installation compared to previous heating patterns.

Table 4.17: Electricity use impacts, Midnight – 5.00 a.m. (*First winter*)

	0 a.m.	1 a.m.	2 a.m.	3 a.m.	4 a.m.	5 a.m.
Outdoor temperature ($Temp^O_{iht}$)	-0.00278	-0.00357	-0.00270	-0.00313	-0.00411*	-0.00337
	(0.00347)	(0.00286)	(0.00260)	(0.00199)	(0.00220)	(0.00338)
Heat pump (HP_{iht})	-0.00712	0.00174	0.00672	-0.0149	-0.0272	0.0222
	(0.0256)	(0.0255)	(0.0352)	(0.0291)	(0.0300)	(0.0410)
Day*CZone fixed effects	YES	YES	YES	YES	YES	YES
Half-hour fixed effects	NO	NO	NO	NO	NO	NO
House fixed effects	YES	YES	YES	YES	YES	YES
R^2	0.617	0.605	0.596	0.558	0.570	0.552
Number of houses	121	121	121	121	121	121
Observations	8,500	8,591	8,593	8,591	8,593	8,590

Notes: Constant included but not reported.
*Standard errors (clustered on households) in parentheses; *** p<0.01, ** p<0.05, * p<0.1.*

Table 4.18: Electricity use impacts, 6.00 a.m. – 11.00 a.m. (*First winter*)

	6 a.m.	7 a.m.	8 a.m.	9 a.m.	10 a.m.	11 a.m.
Outdoor temperature ($Temp^O_{iht}$)	-0.00135	-0.000424	-0.00398	-0.00366	-0.0145*	-0.0139**
	(0.00306)	(0.00401)	(0.00426)	(0.00651)	(0.00801)	(0.00601)
Heat pump (HP_{iht})	-0.0184	-0.00323	-0.0774	-0.0982	-0.125**	-0.106*
	(0.0321)	(0.0521)	(0.0615)	(0.0595)	(0.0594)	(0.0626)
Day*CZone fixed effects	YES	YES	YES	YES	YES	YES
Half-hour fixed effects	NO	NO	NO	NO	NO	NO
House fixed effects	YES	YES	YES	YES	YES	YES
R^2	0.591	0.561	0.547	0.574	0.636	0.561
Number of houses	121	121	121	121	121	121
Observations	8,592	8,593	8,592	8,590	8,590	8,581

Notes: Constant included but not reported.
*Standard errors (clustered on households) in parentheses; *** p<0.01, ** p<0.05, * p<0.1.*

Table 4.19: Electricity use impacts, Midday – 5.00 p.m. (*First winter*)

	12 p.m.	1 p.m.	2 p.m.	3 p.m.	4 p.m.	5 p.m.
Outdoor temperature ($Temp^O_{iht}$)	-0.0166**	-0.025***	-0.025***	-0.0204**	-0.0379**	-0.0243*
	(0.00718)	(0.00797)	(0.00818)	(0.00920)	(0.0153)	(0.0136)
Heat pump (HP_{iht})	-0.0812	-0.101*	-0.0625	-0.0625	-0.0923	-0.155*
	(0.0564)	(0.0538)	(0.0476)	(0.0500)	(0.0615)	(0.0806)
Day*CZone fixed effects	YES	YES	YES	YES	YES	YES
Half-hour fixed effects	NO	NO	NO	NO	NO	NO
House fixed effects	YES	YES	YES	YES	YES	YES
R^2	0.522	0.516	0.512	0.529	0.560	0.621
Number of houses	121	121	121	121	121	121
Observations	8,579	8,587	8,588	8,586	8,589	8,597

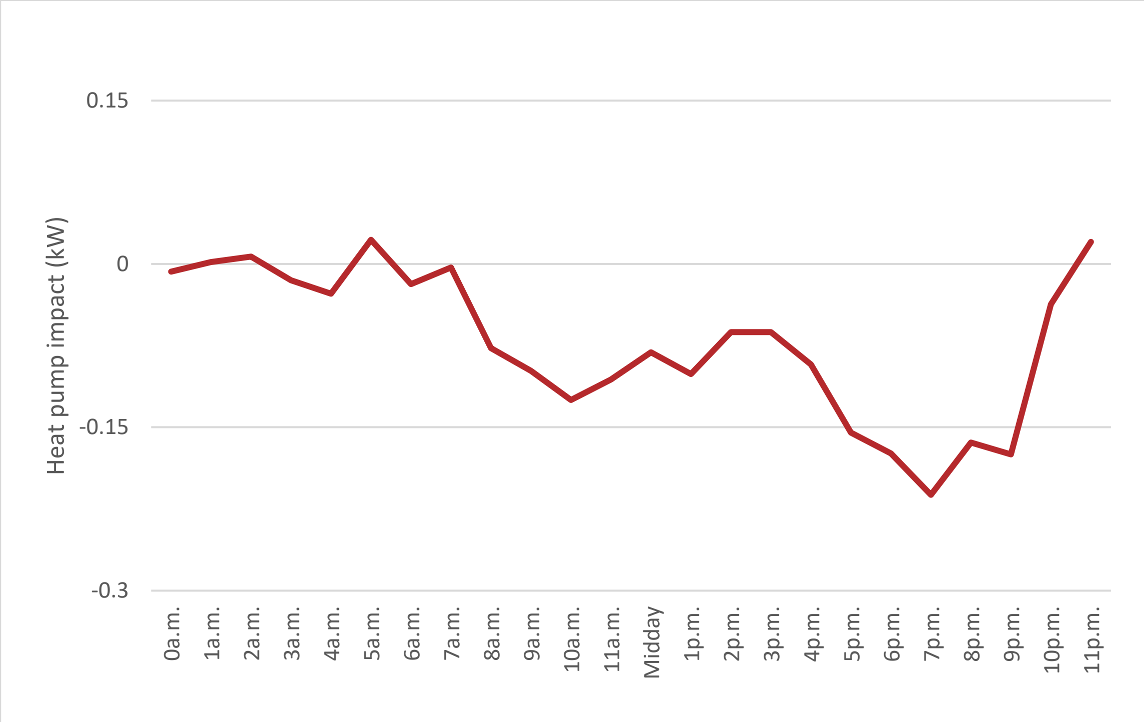
Notes: Constant included but not reported.
*Standard errors (clustered on households) in parentheses; *** p<0.01, ** p<0.05, * p<0.1.*

Table 4.20: Electricity use impacts, 6.00 p.m. – 11.00 p.m. (*First winter*)

	6 p.m.	7 p.m.	8 p.m.	9 p.m.	10 p.m.	11 p.m.
Outdoor temperature ($Temp^O_{iht}$)	-0.0119	-0.0115	-0.00810	-0.0122**	-0.00539	-0.00521
	(0.0131)	(0.0144)	(0.0102)	(0.00547)	(0.00548)	(0.00481)
Heat pump (HP_{iht})	-0.174*	-0.212***	-0.164**	-0.175**	-0.0370	0.0204
	(0.0906)	(0.0789)	(0.0641)	(0.0780)	(0.0494)	(0.0515)
Day*CZone fixed effects	YES	YES	YES	YES	YES	YES
Half-hour fixed effects	NO	NO	NO	NO	NO	NO
House fixed effects	YES	YES	YES	YES	YES	YES
R^2	0.664	0.684	0.665	0.661	0.630	0.690
Number of houses	121	121	121	121	121	121
Observations	8,587	8,596	8,596	8,594	8,595	8,572

Notes: Constant included but not reported.
*Standard errors (clustered on households) in parentheses; *** p<0.01, ** p<0.05, * p<0.1.*

Figure 4.5: Electricity use impact of heat pump by hour of day (*First winter*)



4.3.3 First summer

We investigate whether use of a heat pump as an air conditioner is associated with a change in electricity use over *First summer*. Our specification (with electricity use as the dependent variable) mirrors that used to test for temperature effects of air conditioner use. Hence the equation that we estimate is as follows:

$$Electricity_{iht} = \beta_0 + \beta_1 Temp^O_{iht} + \beta_2 AirCon_{iht} Temp^O_{iht} + \mu_{tc} + \mu_h + \mu_i + \varepsilon_{iht} \qquad (8)$$

Estimates from (8) show no significant change in electricity use as a result of using the heat pump as an air conditioner. As noted in our discussion of temperature impacts of air conditioner use, we only have information on whether a household use their heat pump as an air conditioner over summer with no information on frequency or intensity of use. The insignificant results when estimating (8), together with the modest average temperature changes associated with air conditioning shown above, suggest that even when the heat pump is used as an air conditioner, we are unable to detect whether some houses use more electricity as the estimated effects are based on a diversity of households.

4.3.4 Electricity use – conclusions

These electricity use results are important inputs into the cost benefit analysis that follows. Changes in energy use have a direct resource effect that is taken into account in a CBA, and they also have an externality effect through greenhouse gas emissions that is accounted for within the CBA. We incorporate the estimated average electricity saving of 16% over the (four-month) winter period into the CBA. We do not include further savings in shoulder months (even though heat pumps are likely to be used in many households over April/May and October/November, especially in climate zones 2 and 3). Based on our estimates, we also do not include any electricity consumption effects of heat pump use as an air conditioner over summer.

5: Cost benefit analysis

5.1 Purpose

The cost benefit analysis (CBA) provides a comprehensive analysis of the benefits and costs of installing an energy efficient heater alongside insulation (all homes receiving a heater are insulated as per the insulation component of the programme). A comparative analysis of insulation alone is also provided together with calculation of a BCR (benefit cost ratio) for the full WKH programme (heat pump plus insulation). The CBA updates the Phase 1 CBA that was based solely on secondary data which in turn updated the CBA undertaken in the evaluation of the Warm-up New Zealand: Heat Smart (WUNZ:HS) insulation subsidy programme.[74]

5.2 Methods

The CBA was conducted from a societal perspective and for the first time included a wellbeing component. The societal perspective includes costs and benefits accrued across all domestic stakeholders including government, homeowners and employers, as well as wider society – for example from reduced carbon emissions. Two alternative societal approaches were adopted. The first was based on the wellbeing measure within Treasury's CBAx model, which is based on the work of Smith and Davies (reviewed in section 1), plus energy and carbon saving benefits; we refer to this measure as the wellbeing/energy BCR. The second incorporates direct and indirect health benefits based on outcomes from the WUNZ:HS programme (Preval et al., 2017; Fyfe et al., 2020; Fyfe et al., 2022)[75] in addition to energy and carbon saving benefits; we refer to this measure as the health/energy BCR. An analysis from a fiscal perspective was also undertaken to determine the benefit to cost ratio for present and future government spending only. We stress that the fiscal measures are relevant only for internal budgeting purposes by government and are not measures of societal benefits and costs of the programme. Sensitivity analysis is conducted on different components within the CBA to determine the robustness of the BCRs. A net present value (NPV) of annual savings resulting from the programme (covering installations over the 2020/21 year) is calculated for each component of the CBA, adjusted to Q2 2021 prices.

Costs

The number of houses insulated and the average cost of insulating a house through WKH were obtained from EECA for the period July 2020 – June 2021. Table 5.1 presents a summary of costs.

The opportunity cost of the next best alternative heating source is based on average heater size required to heat the living area of a surveyed WKH participant's home. This is included as a negative cost as it represents a resource saving by virtue of the participant not purchasing an alternative heating appliance. The baseline survey of WKH participants indicated that over 90% of households heated their living area in winter, over 80% using some form of electric heating. The number and size of alternative heaters needed is based on an average of MBIE heating calculator estimates for kilowatts required to heat a WKH household. An annual cost for servicing the heat pump is not included in the base case for the CBA. This is consistent with the analysis conducted in Phase 1 of the WKH evaluation and is also consistent with the treatment of alternative heating sources for which no servicing costs are included. An estimated servicing cost for the heat pump is included in the sensitivity analysis.

Table 5.1: WKH Heating and insulation costs, July 2020-June 2021

Description	**Cost association**	**Source**	**Validity**	**Unit of measurement**	**Notes**
Insulation	government	EECA	High	80% cost per house (average)	Includes ceiling insulation, underfloor insulation, moisture barrier
	household			20% cost per house (average)	
Administration insulation	government	EECA	High	$70 per house	
Insulation incentive payment to service providers	government	EECA	High	4% of EECA subsidy	4% of insulation payment when target for houses insulated met. Fiscal cost only.
Heat pump	government	EECA	High	80% cost per house (average)	80% of the cost of the heat pump, up to a ceiling of $3,000
	household			20% cost per house (average)	20% of the cost of the heat pump, plus any additional amount above the $3,000 cost ceiling
Administration heat pump	government	EECA	m-High	7% of EECA subsidy $ per house (average)	
Heat pump servicing	household	EECA	Medium	$150 per house per year	Discounted at 5% p.a. Measure used for sensitivity analysis only

Benefits

Where possible, benefits have been calculated using data collected from the WKH evaluation: electricity records, living area temperature readings and survey responses. Where benefits are unable to be estimated from the evaluation, they are based on previous studies of similar subsidy programmes. For example, estimates of the number of prescriptions, hospitalisations and deaths avoided as a result of the WKH programme are based on evaluations of WUNZ:HS. Tables 5.2 and 5.3 present a summary of benefits.

Direct health benefits – GP visits, prescriptions and hospitalisations avoided – are calculated per person based on the study population of 2.7 people per household. Indirect health benefits – days off school or work avoided – are based only on the subgroup of interest (school children and working adults) and are calculated using the average number of people per WKH evaluation household that were in that subgroup.[76] The same approach is taken to survival, where Preval et. al. (2017) found a significant improvement in survival (for insulation) only for a subgroup of the WUNZ:HS population: those over 65 years with a previous hospitalisation for circulatory disease. The average number of people aged over 65 years per household is calculated and then scaled to those likely to have a circulatory disease based on prevalence of circulatory disease in the WUNZ:HS population aged over 65.[77]

Wellbeing benefits are calculated per household using the results from this evaluation with respect to improvements to "*living in a cold house*" following heat pump installation. We conservatively attribute wellbeing benefits only to the respondent to avoid any risk of double counting (for instance, if the respondent's answer reflected the views of others in the household). Conservatively, we also attribute the wellbeing benefits only to the winter months (June – September). Electricity and carbon benefits are calculated per household and are also scaled to the winter months only. Where the wellbeing component is included, all other health outcomes pertaining to the heat pump component are excluded to avoid double counting. Where possible, the values listed in the Treasury CBAx tool[78] are assigned to benefits, using the more conservative of values listed and adjusted to Q2 2021 prices using the Reserve Bank inflation calculator.[79] This approach is taken to maintain consistency in valuing the different benefits. Where CBAx values are not available, values are derived from appropriate information sources. For example, the average value per kilowatt energy saved is taken from the MBIE[80] Quarterly Survey of Domestic Energy Price (QSDEP). The price of carbon savings per kilowatt-hour reduction in domestic electricity use is sourced from the EECA website.[81]

Table 5.2 WKH benefits from heat pump installation July 2020-June 2022

Description	Benefit association	Source	Validity	Unit of measurement	Benefit per unit	Notes
Hospital admissions avoided	government	Fyfe (2020), Treasury CBAx tool	Medium	$ per inpatient visit per person year.	$6,100	8.60 visits per 1000 person years.
Pharmaceutical prescriptions avoided (cold associated)	government	Fyfe (2020) Treasury CBAx tool	Medium	$ per prescription avoided per person year.	$34	35.2 per 1000 person years
	household				$5	
GP visits avoided	government	Derived from pharms data Fyfe (2022), Treasury CBAx tool	Medium -Low	$ per visit avoided per person year.	$51	35.2 per 1000 person years.
	household				$40	
Net change in comfort living in a cold house)	household	WKH evaluation, Smith and Davies (2020)	Medium -High	$ per point increase on likert scale per person year[82]	$6,976	Measured per person per year, winter season (June-September only)
Days off work due to sickness	household	Based on insulation measure: WKH evaluation, Preval, (2015), Howden-Chapman et al (2011),[83] Chapman et. al. (2009)	Low	$ per day avoided per household p.a.	$64	0.167 per household with a working adult
Days off work due to caregiving				$ per day avoided per household with a school aged child p.a.	$64	0.180 per household with a school age child where all adults work.
Days of school due to sickness					$58	0.765 per household with-school age child
Net change in electricity consumed	household	WKH evaluation, MBIE survey	Medium	$ per kWh reduction in electricity consumption	$0.29	Based on winter season (June-September only)
Net change in CO_2 from difference in kWh electricity consumed	society	WKH evaluation, EECA report	Medium -Low	$ per kWh reduction in electricity consumption	$0.09	Calculated from the difference in average kWh electricity consumed.

Table 5.3 WKH benefits from insulation installation July 2020-June 2022

Description	Benefit association	Source	Validity	Unit of measurement	Benefit per unit	Notes
Hospital admissions avoided	government	Fyfe (2020), Treasury CBAx tool	Medium	$ per inpatient visit per person year.	$6,100	9.26 per 1000 person years.
Pharmaceutical prescriptions avoided (cold associated)	government	Fyfe (2022) Treasury CBAx tool	Medium	$ per prescription avoided per person year.	$34	17.2 per 1000 person years
	household				$5	
Increase in survival (cold associated)	household	Preval (2017), Treasury CBAx tool	Medium	Value of a life year (VLY) proportion fewer deaths	$34,768	25.3 per 1000 person years for persons over 65 with cardiovascular disease.
GP visits avoided	government	Derived from pharms data Fyfe (2022), Treasury CBAx tool	Medium -Low	$ per visit avoided per person year.	$51	17.2 (17.2-17.4) per 1000 person years
	household				$40	
Net change in comfort (living in a cold house)	household	Based on the heat pump wellbeing measure. CBAx tool	Medium	$ per point increase on liket scale per person year. [84]	$6,976	50% heat pump benefit per household per year (i.e. $3,488 per household)
Days off work due to sickness	household	Preval (2015), Howden-Chapman et al. (2011), Chapman et al. (2009),[85] CBAx tool	Medium	$ per day avoided per household p.a.	$64	0.167 per household with a working adult
Days off work due to caregiving				$ per day avoided per household with a school aged child p.a.	$64	0.180 per household with a school age child where all adults work.
Days of school due to sickness					$58	0.765 per household with-school age child

Validity

Tables 5.1-5.3 include a validity rating for costs and benefits based on the data source from which they were derived. A source based on primary data is considered of higher validity.
An explicit value for wellbeing based on CBAx estimates "*living in a cold house*", could only be identified for the heat pump component of the study. We note from prior studies that the insulation component of the programme also contributes to combatting the effects of "*living in a cold house*" and we have included a wellbeing benefit from insulation in the wellbeing/energy BCR with the contribution from insulation to wellbeing assumed at half that identified for the heat pump.

An explicit value for time off work or school avoided could only be sourced for the insulation component of the study. Noting that having an efficient and effective source of heating is also likely to contribute to fewer days off work or school, we have included these benefits in the health/energy BCR with the benefits assumed to be the same as those accrued from insulation.

Base case scenario

The base case scenario assumes 75% additionality for programme benefits and variable costs (based on the figure used in the CBA of WUNZ:HS); this assumption means that 75% of recipients of the WKH subsidy would not have availed themselves of insulation or a heat pump in the absence of the programme, while 25% would have privately installed these components if the programme had not existed. We use the Treasury recommended discount rate of 5% on costs and benefits accrued over the life of the heat pump (10 years) and insulation (30 years). A 20% fiscal multiplier is applied to (outlays and savings) of government expenditure.

Separate analyses have been undertaken for the whole WKH programme (heat pump and insulation), the heat pump component and the insulation component. Societal BCRs are calculated separately for wellbeing/energy and for health/energy while the fiscal calculations refer only to health/energy.

Summary of key assumptions

The following assumptions are made in calculating the BCRs:

- The demographic characteristics of the evaluation participants reflect those of the WKH population.
- The heat pump lasts for 10 years (the length of warranty) at 100% efficiency.
- The next best alternative to the heat pump - electric (panel) convection heater - lasts for 10 years (the length of warranty on the heat pump) at 100% efficiency.
- Electricity savings from the heat pump only occur over the winter months (June – September).
- There are no reductions in electricity use as a result of retrofitted insulation.[86]
- Carbon savings are derived only from reductions in electricity consumption, e.g. there are no greater gains from households that swapped gas heating for a heat pump.
- The insulation lasts 30 years at 100% efficiency.
- Heat pumps are only installed in fully insulated houses.

- Benefits remain consistent for the life of the heat pump/ insulation.
- Wellbeing benefits derived from avoiding "*living in a cold house*" are scaled to include the winter months only (June – September) and apply to only one person in the household.
- The improvement in wellbeing associated with having insulation is 50% of that identified for the heat pump.
- Reduction in days off work/ school from the heat pump equal those identified for insulation.
- Time off work to care for a preschool/ school aged child is only required if all adults in the household work.
- Survival increases through insulation only, and only for a sub-group of the population who are over 65 years and have a pre-existing circulatory condition.
- Prevalence of circulatory disease in the WKH population that is over 65 years is equivalent to that found in the WUNZ:HS study for the over 65 years population by Preval (2017).
- The number of GP visits required is equal to the number of prescriptions dispensed.

Sensitivity analysis is conducted, varying the following components (individually) to determine robustness of the estimated BCRs:

- Additionality is adjusted to 100% and 50%.
- An (alternative) 2% discount rate, as recommended for sensitivity analysis by Treasury, is applied.
- Costs are adjusted to include $150 p.a. for heat pump servicing.

5.3 Findings

A summary of outcomes based on the central assumptions above are detailed in Table 5.4. More detailed breakdowns of costs and benefits are provided in Tables 5.6a-e.

The base case societal BCRs in Table 5.4 all indicate a net benefit (BCR>1) from the programme as a whole and independently for each of the two components (heat pump and insulation). Whilst the average cost per household is similar for insulation ($2,923) and a heat pump ($2,707), benefits accrue from insulation over a longer period (30 years) compared to 10 years for the heat pump. However, the heat pump also generates benefits from reduced electricity use and reduced carbon emissions. These items represent benefits to the household and the community rather than to government. In addition, government bears the bulk of costs so the fiscal BCRs are less than one in each case. (We again note that the fiscal BCRs are relevant only to government financial flows and are not relevant to considering whether the programme is worthwhile or not.)

Table 5.4: Cost Benefit Analysis: summary table

Base case BCR	Societal perspective	Fiscal perspective*
Whole programme: wellbeing/ energy benefits	4.36	
Whole programme: health/ energy benefits	1.89	0.80
Heat pump: wellbeing/energy benefits	7.49	
Heat pump: health/energy benefits	2.15	0.52
Insulation: wellbeing/energy benefits	3.51	
Insulation: health/energy benefits	1.78	0.98

* The wellbeing/energy approach is not relevant to the fiscal perspective so these cells are left empty.

The base case wellbeing/energy BCR for the full WKH programme based on installations over the 2020/21 year is estimated to be 4.36 representing a saving to society of $189,089,087 at net present value (NPV). The heat pump component, with a wellbeing/energy BCR of 7.49, has a higher BCR than does the insulation component (3.51); however net savings overall are greater from the insulation component (NPV $106,542,290 for 16,201 houses) relative to the heat pump component ($89,232,811 for 9,178 houses) due to the greater number of houses that had insulation installed.

The health/energy BCR for the full WKH programme based on installations over the 202/21 year is 1.89 equating to a saving to society of $49,918,619. Again, the heat pump component has a higher BCR (2.15) than the insulation component (1.78).

Sensitivity analysis

As shown in Table 5.5, at a discount rate of 2%, the BCRs increase across all components (and, from a fiscal perspective, the BCR increases to above one for both the whole programme and for the insulation component). Altering additionality to 50% or 100% makes little difference to the BCRs. Including a $150 p.a. servicing cost for the heat pump reduces the heat pump and overall programme BCRs; however a net societal benefit for each component remains.

Table 5.5: Cost Benefit Analysis: Sensitivity analysis summary table

Societal BCR	**2% discount rate**	**50% additionality**	**100% additionality**	**$150 p.a. service cost**
Societal BCR				
Whole programme: wellbeing/energy	5.70	4.11	4.29	4.15
Whole programme: health/energy	2.44	1.78	1.96	1.80
Heat pump: wellbeing/energy	8.46	7.27	7.60	6.96
Heat pump: Health/ energy	2.43	2.09	2.18	2.00
Insulation: wellbeing/energy	4.97	3.48	3.52	3.51
Insulation: health/ energy expenses	2.42	1.77	1.79	1.78
Fiscal BCR				
Whole programme: health/energy	1.09	0.77	0.81	0.84
Heat pump: Health/ energy	0.59	0.51	0.52	0.52
Insulation: health/ energy expenses	1.39	0.95	1.00	1.00

Comparison to other studies

Whilst a comparative CBA using a wellbeing perspective could not be identified, Liddell and Guiney (2014)[87] developed a framework for measuring the impact of cold and damp homes on mental wellbeing. They formulated a cumulative stressor model based on thermal discomfort, exposure to cold and damp and anxiety around heating costs. New Zealand modelling of the impacts of living in a cold home developed by Smith and Davies were included in the Treasury CBAx tool. However, to our knowledge, this is the first time a wellbeing perspective has been used to investigate an intervention to improve the thermal comfort of housing. A particular strength of this approach is that it encompasses all the interrelated, cumulative, benefits from addressing cold housing in a single measure; from housing quality issues such as dampness and mould, to mental and physical health outcomes and the economic consequences of inefficient heating and poor thermal efficiency.

The current CBA takes a conservative approach in attributing health benefits, resulting in values that are lower than in some previous analyses. For example, the WUNZ:HS CBA estimates and the base case for the Phase 1 WKH evaluation each attributed a higher value to the benefit of survival based on the NZTA estimate, rather than the Pharmac estimate that is used in this evaluation. When the Phase 1 evaluation instead used the Pharmac estimate for value of life, its BCR for insulation (1.83) was very close to the health/energy BCR derived here (1.78). The base case BCR result for the insulation component in this study is also similar to that identified by Chapman et. al. (2009). A follow-up analysis by Preval et al. (2010) examining the impact of providing heaters to households with asthmatic children identified a BCR of 1.09, approximately half that of the health/energy BCR in the current study. The difference is due, in part, to the updated health benefits from reductions in hospitalisations, GP visits and pharmaceuticals dispensed[88] as well as the inclusion of energy and carbon savings in the current evaluation.

5.4 Caveats

A limitation of the estimates presented here is the lack of consistent measures for both health and wellbeing benefits between the heat pump and insulation components of the study. Whilst a wellbeing measure was determined from data collected in the evaluation, collecting similar data for insulation was not within scope of this study. Consequently, the wellbeing benefit for insulation was assessed at 50% of that for heating. This approach was taken based on the premise that whilst benefits to thermal comfort from insulation are well documented, they are less immediate and less visible than those experienced from an efficient and effective heater. Data on the impacts on time off work or school as a result of heat pump installation was also unavailable from prior studies. We attempted to collect these data as part of this evaluation, but these data were considered unreliable due to the effects of the COVID-19 pandemic on work and school attendance over the study period. The corresponding benefits attributed to heating were assumed to be equivalent to those identified for insulation. Related to the caveats above, we do not have information relating to the combined effects of a heat pump and insulation. It is possible, for instance, that one form of treatment may substitute for the other, while it is also possible that each treatment could magnify the other’s effect. In the absence of this information, we have assumed that the effects are simply additive.

Table 5.6a: Base case scenario: 75% additionality, 5% discount rate

Focus	Perspective	Discounted benefits p.a.	Discounted costs p.a.	BCR	NPV
Whole programme	Societal 1: wellbeing & energy	$245,295,539	$56,206,452	4.36	$189,089,087
Whole programme	Societal 2: health & energy	$106,125,071	$56,206,452	1.89	$49,918,619
Whole programme	Fiscal	$45,254,504	$56,746,415	0.80	-$11,491,910
Heat pump component	Societal 1: wellbeing & energy	$102,989,403	$13,756,592	7.49	$89,232,811
Heat pump component	Societal 2: health & energy	$29,571,912	$13,756,592	2.15	$15,815,319
Heat pump component	Fiscal	$9,976,061	$19,263,392	0.52	-$9,287,331
Insulation component	Societal 1: wellbeing	$148,992,150	$42,449,860	3.51	$106,542,290
Insulation component	Societal 2: health	$75,747,119	$42,449,860	1.78	$33,297,259
Insulation component	Fiscal	$36,735,326	$37,483,022	0.98	-$747,696

Table 5.6b: Base case scenario: 75% additionality, 2% discount rate

Focus	Perspective	Discounted benefits p.a.	Discounted costs p.a.	BCR	NPV
Whole programme	Societal 1: wellbeing & energy	$320,211,085	$56,206,452	5.70	$264,004,632
Whole programme	Societal 2: health & energy	$136,953,189	$56,206,452	2.44	$80,746,737
Whole programme	Fiscal	$61,747,959	$56,746,415	1.09	$5,001,545
Heat pump component	Societal 1: wellbeing & energy	$116,383,084	$13,756,592	8.46	$102,626,492
Heat pump component	Societal 2: health & energy	$33,417,712	$13,756,592	2.43	$19,661,120
Heat pump component	Fiscal	$11,273,439	$19,263,392	0.59	-$7,989,953
Insulation component	Societal 1: wellbeing	$210,867,881	$42,449,860	4.97	$168,418,021
Insulation component	Societal 2: health	$102,800,784	$42,449,860	2.42	$60,350,924
Insulation component	Fiscal	$51,991,333	$37,483,022	1.39	$14,508,310

Table 5.6c: Sensitivity analysis: 100% additionality, 5% discount rate

Focus	Perspective	Discounted benefits p.a.	Discounted costs p.a.	BCR	NPV
Whole programme	Societal 1: wellbeing & energy	$327,060,719	$76,275,676	4.29	$250,785,043
Whole programme	Societal 2: health & energy	$141,500,095	$76,275,676	1.96	$65,224,419
Whole programme	Fiscal	$60,339,339	$74,545,516	0.81	-$14,206,177
Heat pump component	Societal 1: wellbeing & energy	$137,319,204	$18,065,094	7.60	$119,254,110
Heat pump component	Societal 2: health & energy	$39,429,215	$18,065,094	2.18	$21,364,121
Heat pump component	Fiscal	$13,301,415	$25,407,494	0.52	-$12,106,079
Insulation component	Societal 1: wellbeing	$198,656,200	$56,373,000	3.52	$142,283,200
Insulation component	Societal 2: health	$100,996,159	$56,373,000	1.79	$44,623,159
Insulation component	Fiscal	$48,980,435	$49,138,022	1.00	-$157,587

Table 5.6d: Sensitivity analysis: 50% additionality, 5% discount rate

Focus	Perspective	Discounted benefits p.a.	Discounted costs p.a.	BCR	NPV
Whole programme	Societal 1: wellbeing & energy	$163,530,360	$39,812,393	4.11	$123,717,966
Whole programme	Societal 2: health & energy	$70,750,048	$39,812,393	1.78	$30,937,654
Whole programme	Fiscal	$30,169,670	$38,947,313	0.77	-$8,777,644
Heat pump component	Societal 1: wellbeing & energy	$68,659,602	$9,448,090	7.27	$59,211,512
Heat pump component	Societal 2: health & energy	$19,714,608	$9,448,090	2.09	$10,266,518
Heat pump component	Fiscal	$6,650,707	$13,119,290	0.51	-$6,468,583
Insulation component	Societal 1: wellbeing	$99,328,100	$28,526,721	3.48	$70,801,379
Insulation component	Societal 2: health	$50,498,079	$28,526,721	1.77	$21,971,359
Insulation component	Fiscal	$24,490,218	$25,828,023	0.95	-$1,337,805

Table 5.6e: Sensitivity analysis: 75% additionality, 5% discount rate, inclusive of $150 p.a. heat pump servicing cost.

Focus	Perspective	Discounted benefits p.a.	Discounted costs p.a.	BCR	NPV
Whole programme	Societal 1: wellbeing & energy	$93,330,290	$57,809,756	1.61	$35,520,534
Whole programme	Societal 2: health & energy	$65,793,373	$57,809,756	1.14	$7,983,617
Whole programme	Fiscal	$47,679,189	$56,746,415	0.84	-$9,067,226
Heat pump component	Societal 1: wellbeing & energy	$33,851,113	$15,359,896	2.20	$18,491,217
Heat pump component	Societal 2: health & energy	$16,000,399	$15,359,896	1.04	$640,503
Heat pump component	Fiscal	$10,065,012	$19,263,392	0.52	-$9,198,380
Insulation component	Societal 1: wellbeing	$59,479,177	$44,287,442	1.34	$15,191,735
Insulation component	Societal 2: health	$49,792,974	$44,287,442	1.12	$5,505,532
Insulation component	Fiscal	$37,614,177	$37,483,022	1.00	$131,154

6: Summary of main findings and future opportunities

The findings of this evaluation indicate that installation of a heat pump through the WKH programme results in households that are more comfortable in their homes, with living areas that are materially warmer and drier in winter. On average, living area temperatures are warmer by 1.1°C during winter for a house with a WKH heat pump fitted relative to one without. These benefits occur at the same time as treated households, on average, reduce their electricity consumption, with reduced electricity use being especially marked in the late afternoon and evening. Households that used their heat pump over summer as an air conditioner also experienced reduced living area temperatures, so increasing their comfort, with no significant increase in electricity consumption.

The benefits experienced by households are reflected in the cost benefit analysis. Our central estimate of the societal benefit cost ratio (BCR) for the WKH heat pump component is 7.49 when our estimates are applied to the wellbeing-based yardsticks in Treasury's cost benefit analysis model (CBAx). Estimates based on more conservative assumptions, which exclude many of the wellbeing gains, show a BCR for WKH heat pump installation of 2.15. Corresponding BCRs for the insulation component are 3.51 and 1.78. For the WKH programme as a whole, the corresponding BCRs are 4.36 and 1.89. Each of the heat pump and installation components, and the wider WKH programme, are therefore estimated to have societal benefits that considerably exceed their costs.

The data gathered through this evaluation enable additional analyses to occur of the impacts of heat pump installation. For instance, we have gathered data on heat pump electricity use that can be matched (half-hourly) to overall household electricity use and temperature outcomes. These data enable greater scrutiny of the performance of the heat pump itself, and of household behaviour including the take-back effect that relates to household decisions regarding the combination of warmth, heat pump use and use of other appliances. Additional analyses could link the subjective warmth responses (from the surveys) to objective changes in living area temperatures and electricity use. Disaggregation of estimates by household and/or house characteristics could reveal differing outcomes of heat pump installation according to household or house type which could be important for targeting of future heating interventions. Researchers (and students) who wish to pursue these and other analyses based on the data are encouraged to contact Motu Research to enquire about possible research extensions. The data have already yielded rich insights, and further insights can be expected using the comprehensive dataset that has been compiled.

Notes

[1] A Summary report, providing less detail (and virtually same Executive Summary), is available as Motu Working Paper 22-13.

[2] Grimes A, Preval N. 2020. Warmer Kiwi Homes Evaluation 2020: Phase 1. Report to EECA. Motu Research, Wellington.

[3] Fyfe, C., Grimes, A., Minehan, S., Taptiklis, P. (2022a). Warmer Kiwis Study: Interim Report. Motu Working Paper 22-02. Wellington, Motu Economic and Public Policy Research.

[4] In Auckland, the mean daily high temperature over May to October months are: May: 17°C, Jun: 15°C, Jul: 14°C, Aug: 15°C, Sep: 16°C, Oct: 17°C. These temperature means indicate that September is only fractionally warmer than June or August.

[5] In Auckland, the mean daily high temperature over November to April months are Nov: 19°C, Dec: 21°C, Jan: 23°C, Feb: 23°C, Mar: 22°C, Apr: 19°C. These temperature means indicate the suitability of treating March as a summer month.

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[15] See: https://www.eeca.govt.nz/co-funding/insulation-and-heater-grants/warmer-kiwi-homes-programme/

[16] Grimes, A., Preval, N., Young, C., Arnold, R., Denne, T., Howden-Chapman, P., & Telfar-Barnard, L. (2016). Does Retrofitted Insulation Reduce Household Energy Use? Theory and Practice. The Energy Journal, 37(4). https://doi.org/10.5547/01956574.37.4.agri.

[17] O'Sullivan K., Viggers H. 2021. Six ways to help fix energy hardship in New Zealand. Policy Quarterly 17(4), 65-72. https://doi.org/10.26686/pq.v17i4.7323

[18] The WKH emphasis on heat pumps as a clean heating device is consistent with modelling work in the UK which demonstrates that mass deployment of heat pumps would help the UK meet its 2050 carbon emission targets. See: Li, X., Arbabi, H., Bennett, G., Oreszczyn, T., Densley Tingley D. (2022) Net zero by 2050: Investigating carbon-budget compliant retrofit measures for the English housing stock. Renewable and Sustainable Energy Reviews, 161.

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[43] The estimates are based on a median equivalised household income of $26,200 expressed in 2019Q1 dollars.
[44] The Treasury's CBAx value for the wellbeing cost of living in a cold home is $6,976, which we scale back (by 0.66) reflecting our estimated effect of heat pump installation on the household's survey response relating to a cold home.
[45] The climate zones are as defined by Standards New Zealand (NZS 4218: 2009). See Fyfe et al. (2020) for a map of New Zealand's climate zones.
[46] Howden-Chapman, P. , Pierse, N., Nicholls, S., Gillespie-Bennett, J., Viggers, H., Cunningham, M.,Phipps, R., Boulic, M., Fjällström, P., Free, S., Chapman, R., Lloyd, B., Wickens, K., Shields, Baker, M., Cunningham, C., Woodward, A., Bullen, C., Crane J., (2008) Effects of improved home heating on asthma in community dwelling children: randomised controlled trial. British Medical Journal. https://doi.org/10.1136/bmj.a1411
[47] https://www.ea.govt.nz/consumers/your-power-data-in-your-hands/my-meter/
[48] https://www.stats.govt.nz/methods/geographic-hierarchy
[49] https://cliflo.niwa.co.nz/
[50] Order of prioritisation is: Māori, Pacific peoples, Asian, MELAA/other, European.
[51] Statistics New Zealand. (2020) Housing in Aotearoa. StatsNZ https://www.stats.govt.nz/reports/housing-in-aotearoa-2020
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[53] Approximately a quarter of households were aware of times of day when energy prices were lower (for example the hour of power) and took advantage of these opportunities, including to heat more rooms in the house.
[54] 5.5% of households used an unflued gas heater to heat the living area which compares 6% who reported using this form of heating in the 2018 New Zealand Census (see Statistics New Zealand. (2020) Housing in Aotearoa. StatsNZ . https://www.stats.govt.nz/reports/housing-in-aotearoa-2020)
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[57] Details on the timing of heat pump installations for the 2021 cohort relative to lockdown periods are provided in Figure 4.1 of the Interim Report.
[58] Qualitative responses (from the 2021 cohort) to a question about satisfaction with the heat pump are included as Appendix 3 in the Interim Report.
[59] We also tested whether the date on which the After survey was undertaken for the household was associated with the heat pump variables finding that it had no significant association.
[60] Bloem R, & Oswald A. 2022. The analysis of human feelings: a practical suggestion for a robustness test. Review of Income and Wealth, 68(3), 689-710.
[61] Recall that extra weeks with a heat pump results in a fall in *HP inverse weeks* so an odds ratio greater than one corresponds to a fall in perceptions of cold as length of installation increases.
[62] Ferrer-i-Carbonell, A. & Frijters P. 2004. How Important is Methodology for the Estimates of the Determinants of Happiness? The Economic Journal, 114, 641-659.
[63] Bond, T. N. and K. Lang (2019) The Sad Truth about Happiness Scales. Journal of Political Economy, 127 (4), 2019, 1629–40.
[64] Data for the week of installation is dropped from the analysis to avoid contamination in results due to uncertainty in the exact timing of installation and to allow for the household to adjust to the new heat pump.
[65] The choice of temperature boundaries (16°C , 18°C , 25°C) reflect those highlighted by Stats NZ in releasing the 2018 General Social Survey results for The Household Energy End-Use Project See: https://www.stats.govt.nz/news/around-a-third-of-homes-too-cold-in-winter-and-too-warm-in-summer#:~:text=The%20Household%20Energy%20End%2DUse,as%20a%20comfortable%20indoor%20temperature.
[66] I.e. we examine the difference in temperature for a house with a heat pump relative to a house without, after heat pump installation relative to before installation. In a standard difference-in-difference specification, we would include a dummy variable for whether the house is in the treated or control group; our inclusion of individual house fixed effects already controls for this factor and so no separate variable is added in any of the

specifications to indicate treatment group. The heat pump variable itself becomes the "Treatment*Post" variable that is included in a standard difference-in-difference equation.
[67] Observations recorded on the day or on 3 days either side of installation are excluded to ensure that all readings are accurately attributed to pre- or post-installation.
[68] In the Interim Report, we tested whether a fieldworker-assessed house condition variable was significant when added as an interaction term to the equation, but no effect was found so it is omitted here (though the effect of house condition on outcomes is still captured through the house fixed effects in our estimates). In the Interim Report we also tested whether our estimates were sensitive to excluding observations where the external temperature was greater than 18ºC (approximately 1% of the sample), finding no material change in estimated coefficients, so all observations are retained here.
[69] The 1.1ºC average gain in temperature is a little lower than that estimated in the Interim Report (1.4ºC). One key modelling change between the interim and final reports is the use of Day*Climate zone fixed effects in the current report as opposed to the use of Day fixed effects in the interim report. The Day*climate zone fixed effects are better able to control for regional lockdowns that occurred over winter 2021, which may have affected the size of the estimated coefficient (and may also have affected the size of the time of day estimates that follow).
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[71] Grimes A, Preval N. 2020. *Warmer Kiwi Homes Evaluation 2020: Phase 1*. Report to EECA, Wellington.
[72] The estimated coefficient on the heat pump variable for equation (5) using the second approach with control houses added is -0.0711 which is almost identical to the -0.0720 coefficient estimated in the absence of the extra control houses.
[73] The Interim Report also estimated a reduction in electricity use but that estimate was not statistically significant (except at particular hours of the day). The current sample is larger than that in the interim report, so enhancing power. In addition, the inclusion of Day*Climate zone fixed effects in the current report as opposed to the prior use of Day fixed effects better controls for regional lockdowns that occurred over winter 2021, and this may have increased the significance of the estimated coefficient.
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[76] The average number of school aged children and working adults per household were 0.27 and 1.25 respectively.
[77] The resulting figure is 0.03 people per household, on average, that are estimated to in this category.
[78] https://www.treasury.govt.nz/information-and-services/state-sector-leadership/investment-management/plan-investment-choices/cost-benefit-analysis-including-public-sector-discount-rates/treasurys-cbax-tool
[79] https://www.rbnz.govt.nz/monetary-policy/about-monetary-policy/inflation-calculator
[80] https://www.mbie.govt.nz/building-and-energy/energy-and-natural-resources/energy-statistics-and-modelling/energy-statistics/energy-prices/electricity-cost-and-price-monitoring/
[81] https://www.eeca.govt.nz/insights/eeca-insights/record-jump-in-energy-and-carbon-savings-from-efficient-product-sales/
[82] Our results indicate that warmth increased by approximately 0.66 of a step on the Likert scale (which is the figure we use in the CBA).
[83] Howden-Chapman, P., Crane, J., Chapman, R., & Fougere, G. (2011). Improving health and energy efficiency through community based housing interventions. International Journal of Public Health, 583-588.
[84] As for the heat pump, this figure is multiplied by 0.66 (and is then halved for the insulation component).

[85] Chapman, R., Howden-Chapman, P., Viggers, H., O'Dea, D., & Kennedy, M. (2009). Retrofitting houses with insulation: A cost-benefit analysis of a randomised community trial. Journal of Epidemiology and Community Health, 63(4), 271–277

[86] Grimes et al. (2016) find that electricity savings following retrofitted insulation are at most 2% (as a result of the take-back effect). Given the small magnitude of these estimated savings, we do not include any benefits from electricity reductions in calculating the benefits that flow from insulation.

[87] Liddell, C., & Guiney, C. (2014). Improving Domestic Energy Efficiency: Frameworks for Understanding the Impacts on Mental Health. *University of Ulster*.

[88] In particular, see Fyfe et al. (2020) and Fyfe et al. (2022).