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Pathways to Net-zero Residential Buildings and Urban Communities in New Zealand

Daniel Bishop, Mahdi Mohkam and Larry Bellamy

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Executive Summary

This report assesses the potential impacts of the 'DEEDs' strategies on operating greenhouse gas (GHG) emissions and energy demands associated with New Zealand's households. Central to New Zealand's plan to reduce household emissions [1], these strategies are:

- Decarbonisation of the electricity system (D)
- Electrification of space heating, water heating and cooking (E)
- Energy efficiency improvements of buildings to reduce energy demand (E)
- Digitalisation to improve energy management of buildings and energy supply systems (D)
- Electrification of vehicles (s)

The 'DEEDs' are assessed at neighbourhood level by modelling the combined energy performance of a cluster of 60 households connected to a low voltage transformer.

Urban Energy Model (UEM)

A physics-based UEM was developed to simulate the energy performance of pseudo neighbourhoods at four locations with significantly different climates: Auckland, Palmerston North, Christchurch and Dunedin. Pseudo neighbourhoods are populated with a range of model house designs, to represent the size distribution of New Zealand's housing stock. Varying levels of insulation are applied to model houses to assess the 'DEEDs' for 'old', 'mixed age' and 'new' neighbourhoods. The initial 'Baseline' scenario represents the level of technological uptake in each of the regions. Interventions and pathways are applied, which change the levels of technological uptake from the baseline, to assess the impact of interventions.

The UEM is an energy systems analysis tool with interconnected modules that model household energy demands (space heating, hot water heating, cooking, and other plug loads), private transport (domestic EV charging), distributed electricity generation (rooftop PV and domestic batteries) and power load control. The UEM predicts energy consumption, operational GHG emissions and time-series power demands for each household and the cluster of households comprising a pseudo neighbourhood. The simulation tool is custom developed software, written in Python and integrates open-source packages such as EnergyPlus and PVlib. The tool is available freely on request; however it is most suitable for technically proficient users.

The 'DEED's' interventions and pathways that are assessed using the UEM are listed in Table 0-1 and the impact of selected interventions and pathways on GHG emissions and peak power loads on the electricity network are shown in Figure 0-1.

Key findings – interventions

Key findings for interventions and pathways are summarised below, where the full descriptions of the interventions are listed in Table 0-1. The most significant finding is large reductions in operational GHG emissions (up to 89%) can be achieved by utilising presently available technologies.

Building energy efficiency

Increased levels of building insulation provide a slight decrease in household electricity consumption and GHG emissions, however this intervention provides a more significant reduction on peak loads for electricity networks, especially in older neighbourhoods and colder climates.

Electrification of buildings

Electrification of space heating, where all wood, gas, and electric resistive heaters are replaced with heat pumps, moderately increases electricity consumption and peak power loads where the current uptake of heat pumps is low.

Electrification of hot water heating, replacing the small levels of gas water heating with electric resistive heating, leads to moderate increases in electricity demand and significant increases in peak power load. However, the use of hot water heat pumps for all hot water heating leads to significant reductions in electricity demand, energy consumption, GHG emissions, and peak power loads.

Wood-fuelled space heating

Greater use of wood burners for space heating leads to a small decrease in emissions and a modest reduction in peak power loads. Overall, it presents a promising strategy, particularly for colder climates, for achieving reductions in GHG emissions while reducing electricity consumption and peak power loads.

Electric vehicles (EVs)

Increased uptake of EVs leads to the greatest reduction of GHG emissions of all the interventions assessed. EV charging without load control significantly increases electricity demand and moderately increases peak power loads, which would require significant upgrades to electrical networks. However, increases in peak power loads can largely be eliminated with smart control of EV charging, without any notable loss in vehicle utility.

PV electricity generation

Increased uptake of distributed PV electricity generation leads to significant reductions in GHG emissions. PV generation can also significantly reduce peak power loads and reduce energy demands on the electricity network.

The use of domestic batteries can produce moderate reductions in peak power loads on the electricity network. Greater reductions than shown in this report are expected by using smart control of household electricity loads based on transformer load feedback rather than household level peak management strategies.

Coupling PV with batteries marginally reduces network electricity consumption and peak power loads compared with PV or batteries alone.

Key findings – pathways

Electrification and wood-fuelled space heating

This pathway combines full electrification of all homes and private transport, except wood burners are used for space heating and heat pumps are used for hot water heating.

This pathway potentially reduces the operating GHG emissions of households by 72% - 80%, depending on the location.

While electricity consumption is slightly higher (9%) in Auckland, it is lower in the three other locations included in this study (Christchurch, Dunedin, Palmerston North). Peak power loads on the electricity network reduce by 8% - 21%.

This pathway has the potential to significantly reduce household emissions without needing to increase the capacity of the electricity network (not considering future growth of household numbers), through the widespread use of established technologies:

- Hot water heat pumps
- Wood burning space heaters
- EVs

Full electrification

This pathway involves full electrification of all homes and private transport, with heat pumps used for space heating and hot water heating.

This pathway also potentially reduces the operating GHG emissions of households by 72% - 80%, depending on location.

Electricity consumption increases 5% - 16%, depending on location, but there is little change in peak power loads on the electricity network.

This pathway also has the potential to significantly reduce household emissions without the need to increase the capacity of the electricity network (not considering future growth of household numbers), through the widespread use of a slightly different set of established technologies:

- Hot water heat pumps
- Heat pump space heaters
- EVs

Electricity consumption increases with this pathway, which would need to be met with additional electricity generation.

Full electrification and PV electricity generation with batteries

This pathway involves full electrification of homes and private transport with the addition of solar PV and domestic batteries.

This pathway potentially reduces the operating GHG emissions of households by 86-89%, depending on location. This pathway produces the greatest reduction in GHG emissions of the three assessed.

Network electricity consumption decreases by 30-33%, but greater reductions can be achieved by increasing PV generation capacity. More importantly, this pathway reduces peak power loads on the electricity network by up to 10%.

This pathway has the greatest potential to reduce household emissions without the need to increase the capacity of the electricity network (not considering future growth of household numbers), through the widespread use of an expanded set of established technologies:

- Hot water heat pumps
- Heat pump space heaters
- EVs
- Solar PV with batteries

In summary, the results show there are technically feasible pathways to significantly reduce GHG emissions from households, without creating overloading problems on electricity networks.

Conclusions

Key technologies identified as playing a significant role in decarbonisation of households include wood heaters, hot water heat pumps, space heating heat pumps, solar PV systems, electric vehicles, and smart load control.

- The widespread uptake of hot water heat pumps can significantly reduce electricity demand, energy consumption, operating GHG emissions, and peak power loads on electricity networks. They are a promising technology for reducing emissions without overloading electricity networks.
- The widespread uptake of wood-fuelled space heaters can produce small reductions in operating GHG emissions but significant reductions in electricity demand and peak power loads on electricity networks. Wood heating frees up capacity on the electricity network to

support the electrification of private transport and are particularly suitable for colder climates.

- The widespread uptake of EVs can significantly reduce operating GHG emissions due to the large fraction of household emissions arising from private transportation. EV's also significantly increase electricity demand and moderately increase peak power loads on the electricity network. However, it appears increases in peak power loads can be largely offset by using smart control of EV charging and other building-related electricity loads.
- Rooftop PV can lead to significant reductions in operating GHG emissions, and a significant share of PV-generated electricity can be consumed within the local network. However, at high levels of uptake, PV generation can produce excess power supply leading to potentially damaging high reverse peak power loads, which presents a risk to be managed.

The three pathways demonstrate that significant reductions in GHG emissions can be achieved through deploying strategic combinations of technologies without increasing peak power loads on the electricity network.

Identifying 'best' combinations of these technologies requires a comprehensive analysis of their economics and impacts, including consideration of embodied GHG emissions, which could be significant for batteries, solar PV, and electric vehicles, and changes in the country's power generation, transmission and distribution requirements. These considerations are outside the scope of this report. However, the report provides direction concerning the energy technologies and strategies that should be considered when assessing various pathways for reducing household GHG emissions.

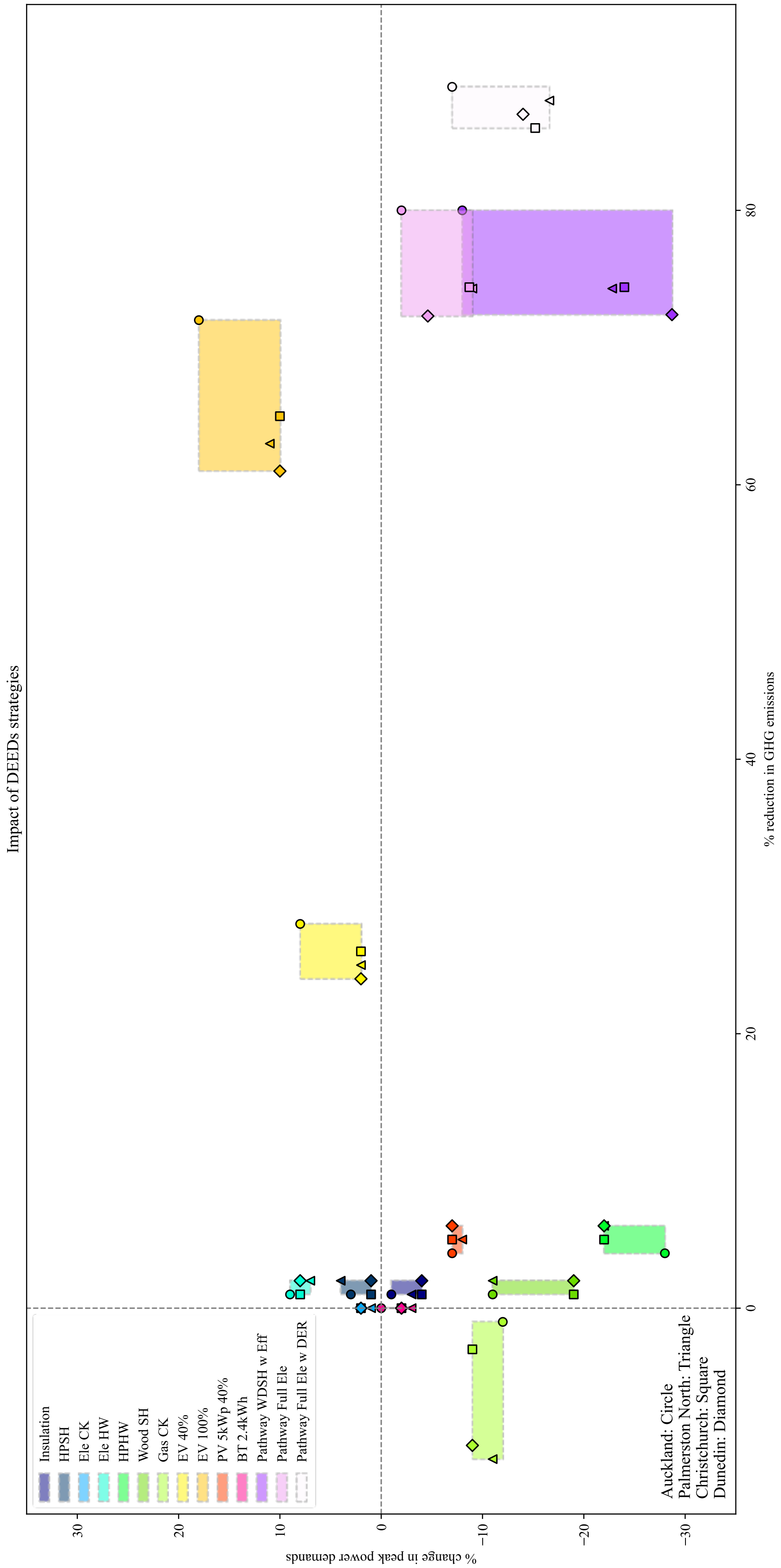

Figure 0-1: Impact of selected interventions and pathways on household GHG emissions and peak power load (95th percentile) on the electricity network

Table 0-1: Selected interventions and pathways for reducing GHG emissions from households

INTERVENTION	DESCRIPTION
Insulation	All households have 2023 Building Code insulation
HPSH	All households have heat pump space heating
Insulation & HPSH	All households have 2023 Building Code insulation and heat pump space heating
Ele CK	All households have electric cooking
Ele HW	All households have electric resistive hot water heating
HPHW	All households have heat pump hot water heating
Wood SH	All households have wood fuelled space heating
Gas CK	All households have gas cooking
EV 40%	40% of private vehicles are electric vehicles
EV 100%	All private vehicles are electric vehicles
PV 5kWp 40%	40% of households have 5kWp solar PV arrays
BT 2.4kWh	All households have 2.4kWh domestic batteries
PV 5kWp & BT 6.4 kWh	All households have 5kWp solar PV arrays 6.4kWh domestic batteries
PATHWAY (combinations of interventions)	
WDSH	All households have wood-fuelled space heating, electric cooking, heat-pump hot water heating with load control, and electric vehicles with load control
Full w Ele	All households have heat pump space heating, electric cooking, heat-pump hot water heating with load control, and electric vehicles with load control
Full Ele w DER	All households have heat pump space heating, electric cooking, heat-pump hot water heating with load control, electric vehicles with load control, 5kWp Solar PV arrays and 6.4kWh domestic batteries

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List of abbreviations

ADMD	After Diversity Maximum Demand
BC	Building Cluster
BEM	Building Energy Model
BRANZ	Building Research Association New Zealand
BT	Battery
CCC	Christchurch City Council
CK	Cooking
COP	Coefficient of Performance
DER	Distributes Energy Resources
DHW	Domestic Hot Water
DR	Demand Response
EECA	Energy Efficiency Conservation Agency
EEUD	Energy End-Use Database
EV	Electric Vehicle
HCS	Household Condition Survey
HEEP	Household Energy End-use Project
HPHW	Heat Pump Hot Water
HPSH	Heat Pump Space Heating
HTS	Household Travel Survey
HW	Hot Water
HWC	Hot Water Cylinder
LDC	Load Distribution Curve
LOD	Level of Detail
LV	Low Voltage
MAE	Mean Absolute Error
MAPE	Mean Absolute Percentage Error
MBIE	Ministry of Building Innovation and Employment
MOT	Ministry of Transport
MUA	Main Urban Area
MV	Medium Voltage
PV	Photovoltaic
SH	Space Heating
SOC	State of Charge
SUA	Secondary Urban Area
SUD	Single Unit Dwellings
TB	Typical Building
TBL	Typical Building Library
TMY	Typical Meteorological Year
UEM	Urban Energy Model
VKT	Vehicle Kilometres Travelled
WDSH	Wood-fueled Space Heating

1. Introduction

New Zealand is committed to reducing greenhouse gas (GHG) emissions to meet a domestic target of net-zero GHG emissions, excluding biogenic methane, by 2050 and an international target under the Paris Agreement to reduce net GHG emissions to 50 per cent below gross 2005 levels by 2030 [1]. Identifying a suite of emissions reduction strategies that provides an 'acceptable' pathway to these targets is a challenge, not the least because it is difficult to assess the impacts of various strategies and combination of strategies due to the complexity of the energy system.

This report focusses on strategies to reduce emissions associated with New Zealand's households, which are approximately 11% of New Zealand's total GHG emissions [1]. The purpose of this report is to assess selected emissions reduction strategies, to inform the design and development of future buildings and energy infrastructure, and to identify potential pathways to net-zero towns and cities.

1.1 Aim and scope

The report's primary aim is to assess the potential impacts of five GHG emissions reduction strategies on the operational GHG emissions and energy demands of residential buildings and urban communities in New Zealand. These strategies ('DEEDs') are:

- Decarbonisation of the electricity system (D)
- Electrification of space heating, water heating and cooking (E)
- Energy efficiency improvements of buildings to reduce energy demand (E)
- Digitalisation to improve energy management of buildings and energy supply systems (D)
- Electrification of vehicles (s)

New Zealand's plan for reducing GHG emissions relies heavily on the 'DEEDs'. This is the main reason for their inclusion in this study. Another reason is they all contribute to the energy performance of buildings, so it makes sense to consider them together.

This report is limited to assessing the impacts of the 'DEEDs' at neighbourhood level, by modelling the combined energy performance of a cluster of 60 households. This represents a 'typical' number of homes connected to a low voltage transformer. Low voltage (LV) transformers step the voltage from 11 kV, used for distribution, down to 230V for use at the household level. They are susceptible to overloading and may need to be upgraded, especially with electrification and distributed PV electricity generation strategies, so are a useful proxy for the impact of the 'DEEDs' on the electricity network. While limited to neighbourhoods, the results of this study can be used to infer the impacts of the 'DEEDs' at district and city levels.

As household energy performance depends on location, due to regional differences in climate and types of energy technologies used in homes, the 'DEEDs' are assessed at four locations. Household energy performance also depends on the age of homes, since building energy efficiency regulations have changed over the years, so the 'DEEDs' are assessed with different home ages.

The domains included in the modelling analysis are: household energy use; household private car use (not accounting for urban form); and distributed electricity generation at household level (i.e. rooftop PV and domestic batteries). Commercially available technologies are modelled, so the emissions reduction strategies considered in the report are immediately implementable.

The key outputs of the modelling analysis are:

- Household cluster power demands, including peak loads and load durations
- Household cluster annual energy consumption, disaggregated by energy type
- Household cluster annual operational carbon emissions (embodied emissions are out of scope)

Embodied emissions and economic feasibility are out of scope for this analysis.

1.2 Report structure

The report is structured as follows. Section 2 describes the overall modelling approach, including how model neighbourhoods are composed and how the urban energy model works. The decarbonisation interventions and pathways assessed in the report are also described in this section. More detailed descriptions of how model neighbourhoods are formed, and the modules comprising the urban energy model, are provided in Appendix Section 5.3 and Section 5.4, respectively. Verification of the modelling methodology is included in Appendix Section 5.6. Section 3 presents and discusses the key results of the interventions and pathways assessed here. Comprehensive results are presented in Appendix Section 5.1. Section 4 presents the conclusions of the study including key takeaways and limitations.

2. Methodology

2.1 Overview of the modelling approach

The approach used to assess the impact of selected 'DEEDs' involves annual energy simulations of Building Clusters (BCs) with a bespoke Urban Energy Model (UEM) developed for this project. BCs characterise the design of homes and the behaviour of occupants, including the use of appliances and private vehicles.

BCs comprise of 60 'old', 'mixed age' or 'new' homes connected to a low voltage transformer. BCs are developed to represent neighbourhoods in four cities (Auckland, Palmerston North, Christchurch and Dunedin) so that 'DEEDs' can be assessed for households throughout the country.

The UEM is a physics-based multi-domain model that includes household loads (space heating, hot water heating, cooking and other plug loads), transport (private vehicle travel), and distributed electricity generation (rooftop solar PV and domestic batteries). The model determines annual energy consumption, annual operating GHG emissions, and time-series power demands for individual households and the whole BC. Where the operating emissions are calculated from the power demand multiplied by a grid-emissions factor, or where a fuel is used the mass of fuel used is multiplied by the fuel's emissions factor.

Variable behaviour and random fluctuations are included in each domain to avoid all households behaving the same way at the same time, which leads to unrealistic aggregate behaviour. Simulations are conducted at a 60 second timesteps to improve modelling accuracy and to enable smart power controllers to be modelled.

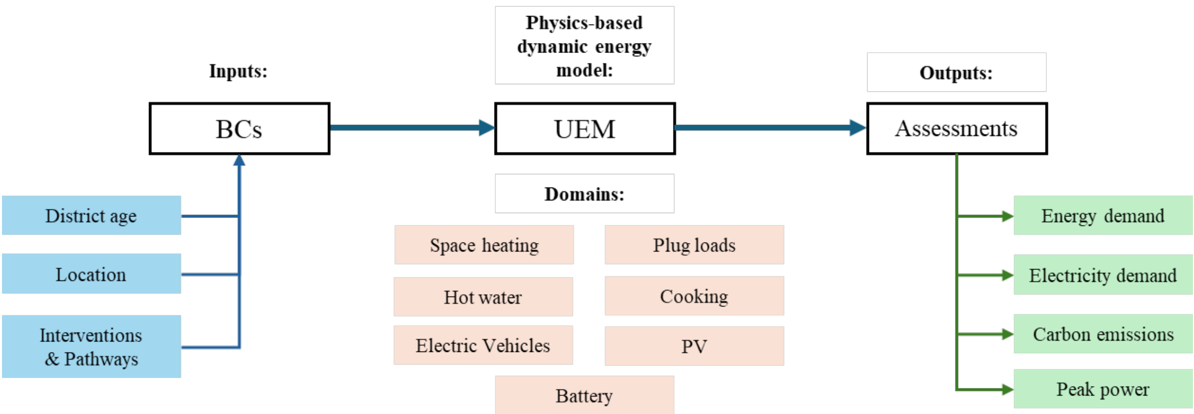

Figure 2-1: Overall modelling approach

The interventions and pathways (combinations of interventions) that were assessed are listed in Table 2-1. The interventions cover a range of technologies and practices that can be implemented now.

Table 2-1: Interventions and pathways for reducing GHG emissions

INTERVENTION	DESCRIPTION
Insulation	All households have 2023 Building Code insulation
HPSH	All households have heat pump space heating
Insulation & HPSH	All households have 2023 Building Code insulation and heat pump space heating
Ele CK	All households have electric cooking
Ele HW	All households have electric resistive hot water heating
Ele HW w LC	All households have electric resistive hot water heating with load control
HPHW	All households have heat pump hot water heating
HPHW w LC	All households have heat pump hot water heating with load control
Wood SH	All households have wood fuelled space heating
Gas CK	All households have gas cooking
Idealistic heating	All households heated to idealistic full-comfort conditions
EV 40%	40% of private vehicles are electric vehicles
EV 40% w LC	40% of private vehicles are electric vehicles with battery charging load control
EV 100%	All private vehicles are electric vehicles
EV 100% w LC	All private vehicles are electric vehicles with battery charging load control
PV 5kWp 40%	40% of households have 5kWp solar PV arrays
PV 5kWp 100%	All households have 5kWp solar PV arrays
BT 2.4kWh	All households have 2.4kWh domestic batteries
BT 6.4kWh	All households have 6.4kWh domestic batteries
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PATHWAY (combinations of interventions)	
WDSH	All households have wood-fuelled space heating, electric cooking, heat-pump hot water heating with load control, and electric vehicles with load control
Full w Ele	All households have heat pump space heating, electric cooking, heat-pump hot water heating with load control, and electric vehicles with load control
Full Ele w DER	All households have heat pump space heating, electric cooking, heat-pump hot water heating with load control, electric vehicles with load control, 5kWp Solar PV arrays and 6.4kWh domestic batteries

2.2 Building clusters

Building Clusters (BCs) are the main input to the UEM. A building cluster describes the buildings, household composition, occupant behaviour, and technological uptake for the 60-household cluster. The BCs listed in Table 2-2 are used to assess the impact of energy interventions and pathways. The clusters represent pseudo-neighbourhoods with attributes (such as distribution of building types, and technological uptake) that mimic the national distribution, or where available, the local region. This approach produces results applicable to regions and the whole country.

Building clusters and inputs for the baseline case are presented in Appendix 5.

The three neighbourhood ages ('old', 'mixed-age' and 'new') capture changes in building energy efficiency over time. Newer neighbourhoods are built to higher energy efficiency standards, which will affect the efficacy of interventions such as building insulation upgrades. 'Old' neighbourhoods are those built before 1969, 'new' are built after 2007, and 'mixed-age' have building ages that approximate the national distribution of building ages.

Table 2-2: Building clusters assessed

LOCATION	DISTRICT AGE
Auckland main urban area	Old (<1969)
	Mixed (Approximates national distribution)
	New (>2007)
Palmerston North main urban area	Old (<1969)
	Mixed (Approximates national distribution)
	New (>2007)
Christchurch main urban area	Old (<1969)
	Mixed (Approximates national distribution)
	New (>2007)
Dunedin main urban area	Old (<1969)
	Mixed (Approximates national distribution)
	New (>2007)

2.3 Urban Energy Model (UEM)

The UEM is a physics-based multi-domain energy model that simulates the energy performance of multiple buildings, minute by minute over a year. It has interconnected dynamic models of buildings, hot water cylinders, electric vehicle batteries, solar PV arrays and domestic batteries. Load control can be implemented on hot water cylinders, electric vehicle charging, and domestic batteries. This means charging and discharging of multiple appliances can be coordinated. The simulation tool is custom developed, written in Python and integrates open-source packages such as EnergyPlus and PVlib. The tool is available freely on request, however, is most suitable for technically proficient users.

The model can simulate multiple households with multiple energy 'components' associated with each household. For example, one household may have one building, one electric hot water cylinder, two electric vehicles, four differently orientated solar arrays and one battery associated with it.

The overall architecture of the UEM is shown in Figure 2-2. A fuller description the Urban Energy Model is included in Appendix 5.

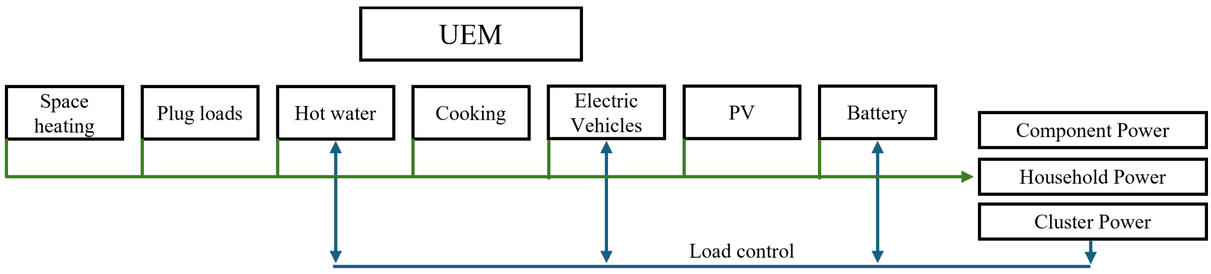

Figure 2-2: Urban energy model architecture

2.4 'DEEDs' interventions and pathways

2.4.1 *Interventions*

Insulation

The insulation intervention upgrades the insulation of all buildings to the R-values in Table 2-3, which reflect the current insulation requirements of the Building Code for the climate zone with the highest insulation requirements. This approach overlooks the different insulation standards for the four locations considered in this study, however the results indicate that building insulation has a relatively minor impact on GHG emissions compared to other interventions. This approach significantly reduces modelling complexity without having a significant impact on overall accuracy.

Table 2-3: R-values used in Insulation intervention

	R-VALUE (W/m^2)
Roof	6.6
Walls	2.0
Floor (on-slab)	1.7
Windows	0.6

Heat pump space heating (HPSH)

This intervention replaces all space heating equipment with heat pumps with a seasonal coefficient of performance equal to 3.8 [2][3].

Insulation with heat pump space heating (insulation & HPSH)

This intervention combines the Insulation and HPSH interventions.

Electric powered cooking (Ele CK)

This intervention replaces all households cooking equipment with electric powered ovens and cooktops.

Electric resistive hot water (Ele HW) and load control (Ele HW w LC)

These interventions replace all hot water heating with electric resistive hot water cylinders, without (Ele HW) or with (Ele HW w LC) load control.

Heat pump hot water (HPHW) and load control (HPHW w LC)

This intervention replaces all hot water heating with hot water heat pumps with a seasonal coefficient of performance equal to 3.5 and heating power to 2.6kW [4][5]. All other parameters are identical to electric resistive hot water cylinders. Load control (LC), when implemented, restricts hot water heating during peak demand hours, i.e. 7am to 9:30am and 5:30pm to 9:30pm.

Wood-fuelled space heating (Wood SH)

This intervention replaces all space heating with wood-fuelled heaters with an efficiency equal to 70%.

Gas-fuelled cooking (Gas CK)

This intervention replaces all cooking appliances with gas-fuelled ovens and cooktops with efficiencies the same as electric cooking.

Idealistic heating

This intervention changes all occupant heating behaviour to 'Idealistic', i.e. full comfort heating throughout the house.

Electric vehicles (EV) and load control (EV w LC)

This intervention increases the penetration of EVs to 40% or 100% of total private vehicles. Vehicle battery capacity is 39 kWh and charging capacity is 7 kW, with full specifications in Section 5.3.4. Load control, where implemented, restricts charging to off peak times, either 9:30pm to 1:30am and 11:30am to 3:30pm, or 1:30am to 5:30am and 11:30am to 3:30pm. These staggered profiles avoid a concentrated power load on the electricity network at 9:30pm.

Solar photovoltaic generation (PV 5kWp)

This intervention increases the penetration of solar PV generation to 40% or 100% of total households. PV arrays have a capacity of 5kWp and temperature coefficient of -0.4%/°C.

Array azimuths and tilts are randomly generated between -45° and +45° and between 10° and 35° respectively. Households with solar PV have only one array (with one set of azimuth and tilt angles).

Domestic battery (BT 2.4kWh and BT 6.4kWh)

This intervention assumes all houses have either a 2.4 kWh or a 6.4 kWh domestic battery. Battery characteristics are summarised in Table 2-4. Domestic batteries are charged during off-peak periods and discharge during other times to reduce peak power loads on the electricity network.

Table 2-4: Battery parameters

Battery capacity (kWh)	2.4 or 6.4
Battery input power capacity (kW)	3.3
Battery output power capacity (kW)	3.3
Battery charging efficiency	0.9
Battery discharge efficiency	0.9

Off-peak times are staggered for each battery, with charging occurring from 9:30pm to 1:30am and 11:30am to 3:30pm or 1:30am to 5:30am and 11:30am to 3:30pm. The staggered profiles avoid creating concentrated peak power loads on the electricity network.

The battery discharging controller considers battery state of charge and the ratio of household power consumption to the peak household power consumption over the last 7 days.

Solar photovoltaic generation and domestic batteries (PV 5kWp & BT 6.4 kWh)

This intervention combines the 100% solar PV intervention with the 6.4 kWh domestic battery intervention. However, battery charging is altered to charge exclusively when there is excess solar PV electricity generation, i,e, when solar PV generation exceeds household power demand.

2.4.2 *Pathways*

Wood space heating with full electrification (WDSH w Ele)

The WDSH w Ele pathway equips all households with wood fuelled space heating, electric cooking, heat-pump hot water heating with load control, and electric vehicles with load control

Full electrification (Full Ele)

The full electric pathway equips all households with heat pump space heating, electric cooking, heat-pump hot water heating with load control, and electric vehicles with load control

Full electrification with distributed energy resources (Full Ele w DER)

The Full Ele w DER pathway equips all households with heat pump space heating, electric cooking, heat-pump hot water heating with load control, electric vehicles with load control, 5kWp Solar PV arrays and 6.4kWh domestic batteries.

2.5 Key modelling assumptions

Key assumptions in the UEM are outlined below.

➔ ***Assessments***
- Grid emissions factor is assumed constant

➔ ***Baseline case – building clusters***
- Building cluster buildings approximates national distribution of buildings
- Technological uptake in the building cluster matches either regional data (where available), or national data

➔ ***Urban energy model***
- Space heating
  - HP have a constant COP, independent of temperature and partial load
- Hot water
  - Daily hot water demand assumed to be 50L per occupant per day
  - Hot Water Cylinders assume a uniform internal temperature
  - HWHPs have a constant COP, independent of temperature and partial load
- Electric vehicles
  - All charging occurs at home
- Plug loads
  - Energy demand from plug loads is independent of household size and occupancy, and instead represents the average national electricity demand due to plug loads
- Cooking
  - Cooking energy demand from plug loads is independent of household size and occupancy, and instead represents the average national electricity demand due to cooking
- PV
  - One set of panels are applied per household, for each household the azimuth angle is assumed to be between -45° and 45° of North. Similarly, tilt angles are assumed to be between 10°and 35°. Where values are randomly generated for each household.

3. Results

This section presents the energy simulation results for selected 'DEEDs' interventions and pathways. Figure 3-1 shows the relative impact of the interventions and pathways on GHG emissions and peak power loads (95th percentile) on the low voltage transformer. Section 3.1 includes results for the baseline case. Sections 3.2 and 0 consider the results for the interventions and Section 3.4 considers the results for the pathways. Results of a study to verify the methodology are included in the Appendices Section 5.5.

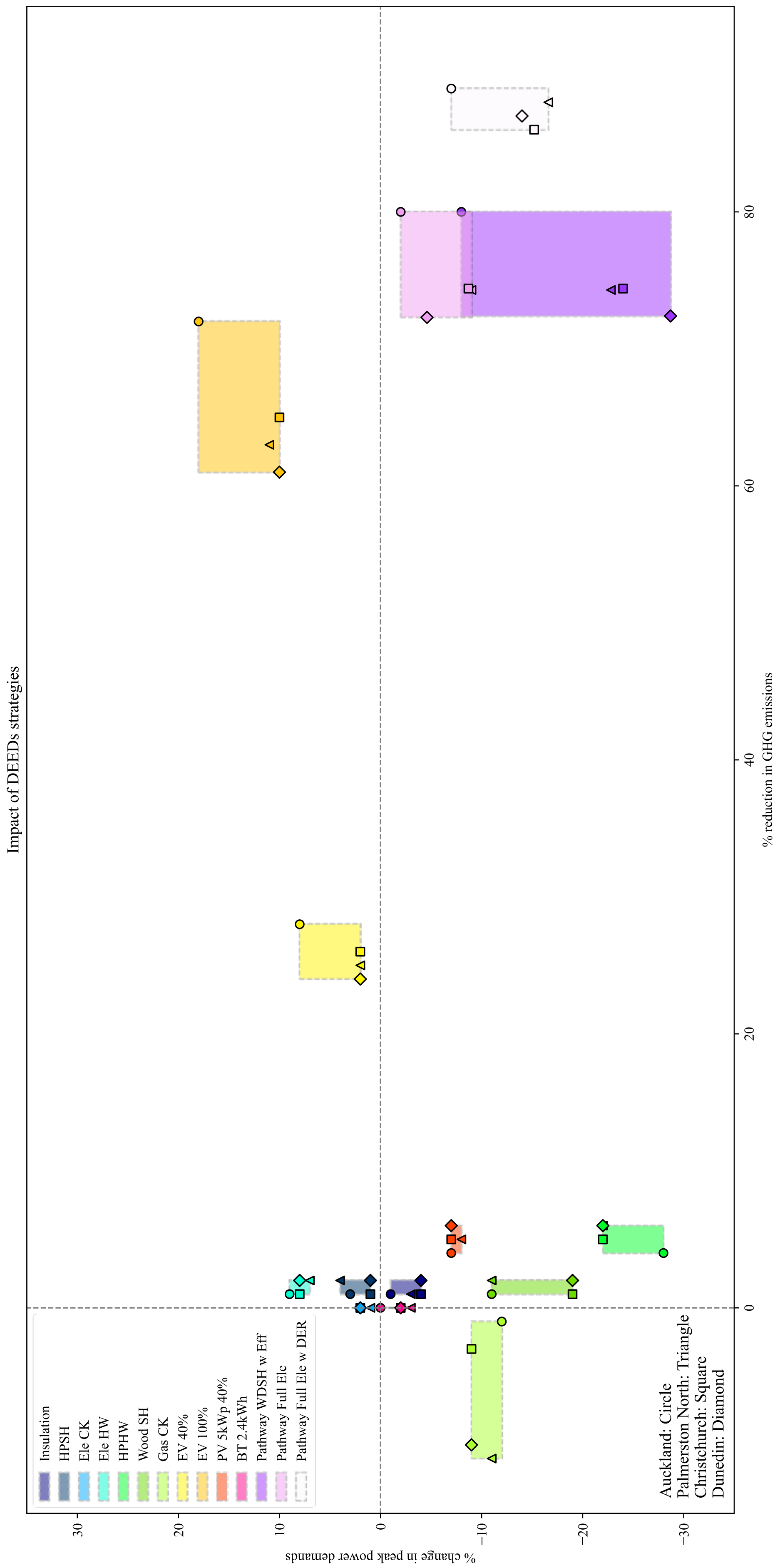

Figure 3 1: Impact of selected interventions and pathways on GHG emissions and peak power loads (95th percentile)

3.1 **Baseline case**

The baseline case is designed to represent the current situation of urban households. Baseline electricity use, energy use, GHG emissions, and peak power loads for the 12 neighbourhoods are shown in Table 3-1.

The results in Table 3-1 show private vehicles do not significantly contribute to household electricity consumption, as there is only 1 EV in baseline BCs. Private vehicles make a significant contribution to household energy consumption (>50%) and GHG emissions (>70%) due to the high emission intensity of transportation fuels. These results highlight the importance of including transportation in the system analysis of the 'DEEDs'.

Transportation energy use and GHG emissions are highest in Auckland and lowest in Dunedin, following the trend in vehicle ownership and vehicle daily travel. These results are for Main Urban Areas (MUAs). Secondary urban areas and rural areas typically have increased vehicle ownership and daily travel distance and hence the trends in non-transportation and transportation energy use will be exaggerated (higher energy use and carbon emissions) for non-MUAs.

Location has a significant effect on non-transportation energy demands, being largest in Dunedin and lowest in Auckland, with similar results for Palmerston North and Christchurch. Differences in non-transportation energy demand are largely due to differences in the locations' climates and space heating technologies. Electricity demands are similar across all locations.

Variations due to the age of homes are low, with the most significant difference in electricity use (2.4%) being observed in Christchurch, and in energy consumption (3.5%) being observed in Dunedin. The minor impact of district age is due to the relatively small difference in space heating demand between different levels of house insulation compared with total electricity use and energy consumption. Differences are most pronounced where colder climates drive greater space heating energy demand (Christchurch and Dunedin).

Peak power loads on the low voltage transformer occur at expected times, i.e. mornings and evenings of the colder months from May to August. There is a trend between maximum power loads and total electricity consumption but no discernible trend between maximum power load and neighbourhood age.

Stochasticity (randomness) is embedded in the UEM to mimic the natural variations in energy use behaviour, so there may be differences in simulation results for a given scenario, despite identical inputs. Multiple simulations of the baseline case are conducted for two cities (Auckland and Dunedin) to determine the variability of results due to stochasticity. Results of this analysis are shown in Table 3-2.

The EV results show a large degree of variability because there is only one EV in the baseline scenario. Unmet hot water demand demonstrates moderate variability (2-3%). Cumulative electricity demand, energy consumption, and GHG emissions demonstrate low variability (<0.3%), which make these results reliable metrics of the impact of a 'DEEDs' intervention. Power demands demonstrate greater variability (1.4-12.4%), with the largest variation seen in minimum and maximum power demands. This indicates care needs to be taken when assessing changes in power demand due to an intervention. There is less variability in the 95th percentile power demand, so this metric and maximum power demand are used to assess the impact on an intervention on the electricity network.

Table 3-1: Summary of baseline case results for cluster of 60 households

BUILDING CLUSTER AGE AND LOCATION		ELECTRICITY TRANSPORT (MWh)	ELECTRICITY NON-TRANSPORT (MWh)	ELECTRICITY TOTAL (MWh)	ENERGY TRANSPORT (MWh)	ENERGY NON-TRANSPORT (MWh)	ENERGY TOTAL (MWh)	CARBON TRANSPORT (T)	CARBON NON-TRANSPORT (T)	CARBON TOTAL (T)	MAX POWER DEMAND (kW)	95th PCT POWER DEMAND (kW)
Auckland	Mixed	1.7	346.3	347.9	654.8	380.2	1035.0	162.8	41.4	204.2	163.8	85.7
	New	1.5	344.5	346.1	654.7	375.0	1029.7	162.8	40.7	203.4	184.8	85.2
	Old	1.5	347.5	349.0	654.7	384.2	1038.9	162.8	41.9	204.6	175.4	87.5
Christchurch	Mixed	1.7	346.5	348.3	654.9	380.5	1035.4	162.8	41.4	204.2	174.5	86.6
	New	1.3	364.6	365.9	516.2	430.3	946.5	128.3	44.1	172.5	171.8	93.5
	Old	1.4	373.4	374.8	516.3	449.0	965.3	128.3	45.7	174.0	205.4	96.2
Dunedin	Mixed	1.1	361.6	362.7	392.9	557.1	950.0	97.7	46.9	144.6	181.9	92.6
	New	1.2	357.2	358.5	393.1	537.3	930.4	97.7	45.8	143.5	184.1	92.4
	Old	1.0	365.3	366.3	392.9	570.5	963.4	97.7	47.6	145.2	179.4	93.4
Palmerston North	Mixed	1.2	347.4	348.6	413.3	461.5	874.8	102.7	44.0	146.7	165.8	87.2
	New	1.2	344.6	345.8	413.4	450.4	863.8	102.7	43.3	146.0	182.8	86.1
	Old	1.3	348.4	349.7	413.4	470.0	883.5	102.7	44.8	147.6	172.3	87.9
	Average	1.4	353.9	355.3	505.9	453.9	959.7	125.7	44.0	169.7	178.5	89.5
Average/household (kWh)				**5.921**			**15.995**	**2.096**	**0.733**	**2.829**	**2.975**	

Table 3-2: Variability of baseline case results for Auckland and Dunedin mixed age cluster of 60 households due to stochasticity

	ELECTRICITY TRANSPORT (MWh)	ELECTRICITY NON-TRANSPORT (MWh)	ELECTRICITY TOTAL (MWh)	ENERGY TRANSPORT (MWh)	ENERGY NON-TRANSPORT (MWh)	ENERGY TOTAL (MWh)	CARBON TRANSPORT (T)	CARBON NON-TRANSPORT (T)	CARBON TOTAL (T)	MAX POWER DEMAND (kW)	95th PCT POWER DEMAND (kW)	50th PCT POWER DEMAND (kW)	MIN POWER DEMAND (kW)	UNMET HW DEMAND (L.min)	UNMET EV TRANSPORTATION DEMAND (km)
Auckland	1.9	346.2	348.2	655.1	380.2	1035.3	162.8	41.4	204.2	163.1	84.2	33.6	8.3	-247959.3	564.1
	1.7	346.6	348.4	654.9	380.6	1035.5	162.8	41.4	204.2	167.9	86.2	33.2	7.5	-244353.8	679.4
	1.5	346.4	347.9	654.7	380.3	1035.0	162.8	41.4	204.2	165.1	85.7	33.4	7.9	-249266.4	602.3
	1.5	345.9	347.4	654.7	379.9	1034.6	162.8	41.4	204.1	164.3	87.4	33.0	8.0	-245506.2	341.7
Auckland variability	24.1%	0.2%	0.3%	0.1%	0.2%	0.1%	0.0%	0.2%	0.0%	2.9%	3.7%	1.8%	9.4%	2.0%	61.8%
Dunedin	1.2	361.7	362.9	393.0	557.2	950.2	97.7	46.9	144.6	169.7	91.6	34.5	8.5	-249089.2	650.0
	1.3	361.7	363.0	393.1	557.2	950.3	97.7	46.9	144.6	161.6	91.3	34.5	8.2	-248063.5	788.8
	1.2	361.6	362.8	393.1	557.1	950.2	97.7	46.9	144.6	183.0	93.5	34.0	8.1	-241752.5	117.5
	1.2	361.9	363.1	393.0	557.4	950.4	97.7	47.0	144.6	176.7	93.3	34.1	7.5	-245651.2	1145.5
Dunedin variability	8.4%	0.1%	0.1%	0.0%	0.1%	0.0%	0.0%	0.1%	0.0%	12.4%	2.4%	1.4%	11.7%	3.0%	152.2%

3.2 Intervention results

This section provides relative results for the interventions listed in Section 2.4. Absolute results are presented in Appendix 5.1. Results are presented for each location for 'mixed age' BCs. Results for all three neighbourhood ages are considered for building energy efficiency interventions, as these interventions are sensitive to age. Discussion of results is provided in Section 0.

3.2.1 *Auckland*

Table 3-3: Relative change from baseline case for energy interventions on a cluster of 60 households in a mixed age neighbourhood at Auckland

INTERVENTION	ELECTRICITY TRANSPORT (%)	ELECTRICITY NON-TRANSPORT (%)	ELECTRICITY TOTAL (%)	ENERGY TRANSPORT (%)	ENERGY NON-TRANSPORT (%)	ENERGY TOTAL (%)	CARBON TRANSPORT (%)	CARBON NON-TRANSPORT (%)	CARBON TOTAL (%)	MAX POWER DEMAND (%)	95th PCT POWER DEMAND (%)
Baseline		0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Insulation		-1%	-1%	0%	-3%	-1%	0%	-3%	-1%	-2%	-1%
HPSH		-1%	-1%	0%	-3%	-1%	0%	-4%	-1%	6%	3%
Insulation & HPSH		-2%	-2%	0%	-5%	-2%	0%	-5%	-1%	0%	-3%
Ele CK		1%	1%	0%	0%	0%	0%	-1%	0%	2%	2%
Ele HW		7%	7%	0%	6%	2%	0%	6%	1%	14%	9%
Ele HW w LC		6%	6%	0%	6%	2%	0%	5%	1%	28%	22%
HPHW		-25%	-25%	0%	-23%	-8%	0%	-22%	-4%	-9%	-28%
HPHW w LC		-25%	-25%	0%	-23%	-9%	0%	-22%	-4%	-12%	-23%
Wood SH		-8%	-8%	0%	27%	10%	0%	-4%	-1%	-9%	-11%
Gas CK		-7%	-7%	0%	0%	0%	0%	6%	1%	-6%	-12%
Idealistic heating		4%	4%	0%	10%	4%	0%	5%	1%	5%	5%
EV 40%	3464%	0%	16%	-30%	0%	-19%	-36%	0%	-28%	14%	8%
EV 40% w LC	3434%	0%	16%	-31%	0%	-19%	-36%	0%	-28%	6%	9%
EV 100%	8773%	0%	41%	-78%	0%	-49%	-91%	0%	-72%	21%	18%
EV 100% w LC	8785%	0%	42%	-78%	0%	-49%	-91%	0%	-72%	5%	13%
PV 5kWp 40%		0%	0%	0%	0%	0%	0%	-19%	-4%	16%	-7%
PV 5kWp 100%		0%	0%	0%	0%	0%	0%	-46%	-9%	5%	-13%
BT 2.4kWh		0%	0%	0%	0%	0%	0%	0%	0%	-3%	0%
BT 6.4kWh		0%	0%	0%	0%	0%	0%	0%	0%	-4%	-3%
PV 5kWp & BT 6.4 kWh		0%	0%	0%	0%	0%	0%	-46%	-9%	-8%	-16%

3.2.2 *Palmerston North*

Table 3-4: Relative change from baseline case for energy interventions on a cluster of 60 households in a mixed age neighbourhood at Palmerston North

INTERVENTION	ELECTRICITY TRANSPORT (%)	ELECTRICITY NON-TRANSPORT (%)	ELECTRICITY TOTAL (%)	ENERGY TRANSPORT (%)	ENERGY NON-TRANSPORT (%)	ENERGY TOTAL (%)	CARBON TRANSPORT (%)	CARBON NON-TRANSPORT (%)	CARBON TOTAL (%)	MAX POWER DEMAND (%)	95th PCT POWER DEMAND (%)
Baseline		0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Insulation		-2%	-2%	0%	-6%	-3%	0%	-5%	-1%	4%	-3%
HPSH		3%	3%	0%	-17%	-9%	0%	-6%	-2%	4%	4%
Insulation & HPSH		0%	0%	0%	-19%	-10%	0%	-8%	-2%	13%	0%
Ele CK		1%	1%	0%	0%	0%	0%	-1%	0%	0%	1%
Ele HW		7%	7%	0%	5%	3%	0%	6%	2%	6%	7%
Ele HW w LC		6%	7%	0%	5%	3%	0%	5%	2%	26%	15%
HPHW		-25%	-25%	0%	-19%	-10%	0%	-21%	-6%	-3%	-22%
HPHW w LC		-25%	-25%	0%	-19%	-10%	0%	-21%	-6%	-15%	-22%
Wood SH		-8%	-8%	0%	21%	11%	0%	-7%	-2%	-14%	-11%
Gas CK		-7%	-7%	14%	0%	7%	14%	5%	11%	0%	-11%
Idealistic heating		2%	2%	0%	20%	11%	0%	19%	6%	9%	4%
EV 40%	3102%	0%	11%	-30%	0%	-14%	-36%	0%	-25%	11%	2%
EV 40% w LC	3010%	0%	10%	-31%	0%	-14%	-36%	0%	-25%	0%	-2%
EV 100%	7937%	0%	28%	-76%	0%	-36%	-90%	0%	-63%	12%	11%
EV 100% w LC	7683%	0%	27%	-77%	0%	-36%	-90%	0%	-63%	9%	4%
PV 5kWp 40%		0%	0%	0%	0%	0%	0%	-18%	-5%	0%	-8%
PV 5kWp 100%		0%	0%	0%	0%	0%	0%	-44%	-13%	-2%	-13%
BT 2.4kWh		0%	0%	0%	0%	0%	0%	0%	0%	2%	-3%
BT 6.4kWh		0%	0%	0%	0%	0%	0%	0%	0%	-2%	-3%
PV 5kWp & BT 6.4 kWh		0%	0%	0%	0%	0%	0%	-44%	-13%	-13%	-16%

3.2.3 *Christchurch*

Table 3-5: Relative change from baseline case for energy interventions on a cluster of 60 households in a mixed age neighbourhood at Christchurch

INTERVENTION	ELECTRICITY TRANSPORT (%)	ELECTRICITY NON-TRANSPORT (%)	ELECTRICITY TOTAL (%)	ENERGY TRANSPORT (%)	ENERGY NON-TRANSPORT (%)	ENERGY TOTAL (%)	CARBON TRANSPORT (%)	CARBON NON-TRANSPORT (%)	CARBON TOTAL (%)	MAX POWER DEMAND (%)	95th PCT POWER DEMAND (%)
Baseline		0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Insulation		-3%	-3%	0%	-6%	-3%	0%	-5%	-1%	-8%	-4%
HPSH		1%	1%	0%	-10%	-5%	0%	-5%	-1%	-8%	1%
Insulation & HPSH		-3%	-3%	0%	-13%	-6%	0%	-8%	-2%	-14%	-4%
Ele CK		1%	0%	0%	0%	0%	0%	-1%	0%	4%	2%
Ele HW		7%	7%	0%	6%	3%	0%	6%	1%	-2%	8%
Ele HW w LC		6%	6%	0%	5%	2%	0%	5%	1%	10%	12%
HPHW		-23%	-23%	0%	-20%	-9%	0%	-20%	-5%	-13%	-22%
HPHW w LC		-24%	-24%	0%	-20%	-9%	0%	-20%	-5%	-15%	-20%
Wood SH		-14%	-14%	0%	46%	21%	0%	-6%	-1%	-21%	-19%
Gas CK		-7%	-7%	2%	0%	1%	2%	5%	3%	-10%	-9%
Idealistic heating		8%	8%	0%	15%	7%	0%	9%	2%	12%	12%
EV 40%	3164%	0%	12%	-30%	0%	-16%	-35%	0%	-26%	-3%	2%
EV 40% w LC	3118%	0%	12%	-30%	0%	-16%	-35%	0%	-26%	-5%	3%
EV 100%	8028%	0%	31%	-75%	0%	-40%	-88%	0%	-65%	3%	10%
EV 100% w LC	7957%	0%	31%	-75%	0%	-40%	-88%	0%	-65%	1%	6%
PV 5kWp 40%		0%	0%	0%	0%	0%	0%	-19%	-5%	-5%	-7%
PV 5kWp 100%		0%	0%	0%	0%	0%	0%	-45%	-12%	-6%	-13%
BT 2.4kWh		0%	0%	0%	0%	0%	0%	0%	0%	-10%	-2%
BT 6.4kWh		0%	0%	0%	0%	0%	0%	0%	0%	-9%	-4%
PV 5kWp & BT 6.4 kWh		0%	0%	0%	0%	0%	0%	-45%	-12%	-1%	-15%

3.2.4 *Dunedin*

Table 3-6: Relative change from baseline case for energy interventions on cluster of 60 households in a mixed age neighbourhood at Dunedin

INTERVENTION	ELECTRICITY TRANSPORT (%)	ELECTRICITY NON-TRANSPORT (%)	ELECTRICITY TOTAL (%)	ENERGY TRANSPORT (%)	ENERGY NON-TRANSPORT (%)	ENERGY TOTAL (%)	CARBON TRANSPORT (%)	CARBON NON-TRANSPORT (%)	CARBON TOTAL (%)	MAX POWER DEMAND (%)	95th PCT POWER DEMAND (%)
Baseline		0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Insulation		-3%	-3%	0%	-9%	-5%	0%	-6%	-2%	-8%	-5%
HPSH		7%	7%	0%	-26%	-16%	0%	-6%	-2%	6%	8%
Insulation & HPSH		2%	2%	0%	-29%	-17%	0%	-10%	-3%	-9%	1%
Ele CK		1%	1%	0%	0%	0%	0%	0%	0%	-3%	1%
Ele HW		7%	7%	0%	4%	3%	0%	5%	2%	4%	5%
Ele HW w LC		6%	6%	0%	4%	2%	0%	5%	2%	20%	16%
HPHW		-24%	-24%	0%	-16%	-9%	0%	-19%	-6%	-9%	-21%
HPHW w LC		-24%	-24%	0%	-16%	-9%	0%	-19%	-6%	-17%	-21%
Wood SH		-12%	-12%	0%	28%	17%	0%	-7%	-2%	-22%	-17%
Gas CK		-7%	-7%	13%	0%	5%	13%	5%	10%	-12%	-9%
Idealistic heating		7%	7%	0%	21%	12%	0%	11%	3%	-1%	7%
EV 40%	3249%	0%	10%	-30%	0%	-12%	-35%	0%	-24%	-4%	3%
EV 40% w LC	3182%	0%	9%	-30%	0%	-12%	-36%	0%	-24%	-7%	0%
EV 100%	8288%	0%	25%	-77%	0%	-32%	-90%	0%	-61%	-2%	6%
EV 100% w LC	8133%	0%	24%	-77%	0%	-32%	-91%	0%	-61%	7%	4%
PV 5kWp 40%		0%	0%	0%	0%	0%	0%	-18%	-6%	4%	-5%
PV 5kWp 100%		0%	0%	0%	0%	0%	0%	-44%	-14%	3%	-13%
BT 2.4kWh		0%	0%	0%	0%	0%	0%	0%	0%	-11%	-4%
BT 6.4kWh		0%	0%	0%	0%	0%	0%	0%	0%	-7%	-4%
PV 5kWp & BT 6.4 kWh		0%	0%	0%	0%	0%	0%	-44%	-14%	-10%	-16%

3.3 Discussion of intervention results

3.3.1 *Building energy efficiency and takeback effect*

Results for the building energy efficiency intervention for different neighbourhood ages are shown in Table 3-7. Results for the idealistic heating intervention (i.e. full comfort heating through the whole house), used to assess the takeback effect, are shown in Table 3-8.

Table 3-7: Relative change from the baseline case for building energy efficiency interventions on a cluster of 60 households in varying age neighbourhoods at four locations

	INTERVENTION	NEIGHBOURHOOD AGE	ELECTRICITY TOTAL (%)	ENERGY TOTAL (%)	CARBON TOTAL (%)	MAX POWER DEMAND (%)	95th PCT POWER DEMAND (%)
AUCKLAND	Insulation	Mixed	-1%	-1%	-1%	-2%	-1%
		New	-1%	-1%	0%	-13%	-1%
		Old	-2%	-2%	-1%	-9%	-3%
	HPSH	Mixed	-1%	-1%	-1%	6%	3%
		New	-1%	-1%	-1%	-7%	1%
		Old	-1%	-2%	-1%	3%	1%
	Insulation & HPSH	Mixed	-2%	-2%	-1%	0%	-3%
		New	-1%	-1%	-1%	-12%	-3%
		Old	-2%	-2%	-1%	-7%	-5%
PALMERSTON NORTH	Insulation	Mixed	-2%	-3%	-1%	4%	-3%
		New	-1%	-2%	-1%	-6%	-2%
		Old	-2%	-4%	-2%	0%	-4%
	HPSH	Mixed	3%	-9%	-2%	4%	4%
		New	3%	-9%	-2%	-1%	3%
		Old	3%	-10%	-2%	10%	6%
	Insulation & HPSH	Mixed	0%	-10%	-3%	14%	0%
		New	1%	-9%	-2%	3%	1%
		Old	0%	-11%	-3%	9%	-1%
CHRISTCHURCH	Insulation	Mixed	-3%	-3%	-1%	-8%	-4%
		New	-2%	-2%	-1%	2%	-2%
		Old	-4%	-4%	-2%	-15%	-5%
	HPSH	Mixed	1%	-5%	-1%	-8%	2%
		New	1%	-4%	-1%	12%	-1%
		Old	1%	-5%	-2%	-13%	1%
	Insulation & HPSH	Mixed	-3%	-6%	-2%	-14%	-4%
		New	-1%	-5%	-2%	-4%	-3%
		Old	-4%	-7%	-3%	-20%	-6%
DUNEDIN	Insulation	Mixed	-3%	-5%	-2%	-8%	-5%
		New	-2%	-3%	-1%	-9%	-5%
		Old	-4%	-7%	-2%	-7%	-6%
	HPSH	Mixed	6%	-16%	-2%	6%	8%
		New	6%	-15%	-2%	8%	7%
		Old	6%	-16%	-2%	4%	9%
	Insulation & HPSH	Mixed	2%	-17%	-3%	-9%	1%
		New	3%	-16%	-2%	-10%	2%
		Old	1%	-19%	-4%	-8%	1%

Building energy efficiency interventions include higher levels of insulation and 100% uptake of heat pump space heating. Overall, significant reductions can be seen in energy consumption (-1% to -19%) and small but consistent reductions in GHG emissions across all scenarios and interventions (-1 to -4%). Decreases were largest in colder climates (Christchurch and Dunedin), where heat pumps have lower penetration, and in older homes with lower levels of insulation.

Upgraded insulation leads to small decreases in total electricity consumption (-1% to -4%) and slightly greater decreases in peak loads (-1% to 6%, 95th pct), following the same trends as with energy consumption. Electrification of space heating with heat pumps leads to a small decrease to moderate increase in electricity consumption (-1% to +6%), due to the substitution of wood and gas heating. In almost all cases peak demand increases moderately (-1% to +9%, 95th pct).

Combining insulation with heat pumps tends to slight increases or decreases in total electricity consumption (-4% to +3%) and generally leads to decreased peak loading (-6% to +2%, 95th pct). Introducing thermal storage into heat-pump systems could be used to gain the advantages of heating electrification without increases in peak loading. For example, charging an underfloor heating concrete slabs during off-peak times to provide heating during on peak times or using a hot water heat pump to store hot water during off-peak times and releasing that heat into the space during on-peak times with fan coil units can be methods to electrify space heating and access demand-flexibility.

Table 3-8: Relative change from the baseline case for idealistic heating intervention for a cluster of 60 households in mixed age neighbourhoods at four locations

INTERVENTION		ELECTRICITY TOTAL (%)	ENERGY TOTAL (%)	CARBON TOTAL (%)	MAX POWER DEMAND (%)	95th PCT POWER DEMAND (%)
Idealistic heating	Auckland	3%	4%	1%	5%	5%
	Palmerston North	2%	11%	6%	9%	4%
	Christchurch	7%	7%	2%	12%	12%
	Dunedin	6%	12%	3%	-1%	7%

A shift to all households heating “idealistically” (i.e. full comfort) shows the potential takeback effect on space heating when heating costs are reduced due to increased levels of insulation and/or reduced energy costs. With this intervention, significant increases can be seen in energy consumption (4% to 12%) and peak loads (4% to 12%, 95th pct). The magnitude of these results match or exceed the range of results seen with efficiency upgrades, so it is possible that behavioural changes can offset any reductions in electricity consumption, energy demand, GHG emissions and peak power demands due to higher levels of insulation. In the case of the electrification of space heating, the combination of behavioural changes could lead to significant increases in peak demands.

3.3.2 *Electrification*

Table 3-9: Relative change from the baseline case for electrification interventions for a cluster of 60 households in mixed age neighbourhoods at four locations

	INTERVENTION	ELECTRICITY TOTAL (%)	ENERGY TOTAL (%)	CARBON TOTAL (%)	MAX POWER DEMAND (%)	95TH PCT POWER DEMAND (%)	UNMET HW DEMAND/VKL (%)
AUCKLAND	Ele CK	1%	0%	0%	2%	2%	0%
	Ele HW	7%	0%	-1%	14%	9%	-7%
	Ele HW w LC	6%	0%	-1%	28%	22%	43%
	HPHW	-25%	-10%	-6%	-9%	-28%	-14%
	HPHW w LC	-25%	-11%	-6%	-12%	-23%	61%
PALMERSTON NORTH	Ele CK	1%	0%	0%	0%	1%	0%
	Ele HW	7%	0%	-1%	6%	7%	-9%
	Ele HW w LC	7%	0%	-1%	26%	15%	43%
	HPHW	-25%	-13%	-9%	-3%	-22%	-15%
	HPHW w LC	-25%	-13%	-9%	-15%	-22%	31%
CHRISTCHURCH	Ele CK	0%	0%	0%	4%	2%	0%
	Ele HW	7%	0%	-1%	-2%	8%	-7%
	Ele HW w LC	6%	0%	-1%	10%	12%	42%
	HPHW	-24%	-11%	-8%	-13%	-22%	-18%
	HPHW w LC	-24%	-11%	-8%	-15%	-20%	32%
DUNEDIN	Ele CK	1%	0%	0%	-3%	1%	-2%
	Ele HW	7%	0%	-1%	4%	5%	-7%
	Ele HW w LC	6%	0%	-1%	20%	16%	42%
	HPHW	-24%	-11%	-9%	-9%	-21%	-15%
	HPHW w LC	-24%	-11%	-9%	-17%	-21%	33%

The impact of electrification appears to be largely independent of location. This is due to the baseline case assuming that gas hot water heating and gas cooking uptake is a uniform fraction of households throughout the country, as regional data on the uptake of gas appliances was lacking. (See Appendix Section 5.3 for the derivation of technological uptakes for different technologies). For regions with higher gas cooking and water heating uptake than the national average, electrification of these loads will lead to increased electricity load and maximum power demands, and further reductions in GHG emissions than the results here indicate.

A switch to all electric cooking results in a small increase in electricity consumption (~1%) and peak loading (2% ,95th pct). This small impact is likely due to the small proportion of households with gas cooking in the baseline case (8.3%).

A switch to all electric hot water heating without load control results in moderate increases in electricity consumption (~7%) and peak power demands (5-9%, 95th pct). Load control increases peak power demand by 12%-22%, due to restricted heating times reducing the water temperatures in HWCs and hence when switched back on a large portion of HWCs switch on simultaneously (see Figure 3-2). This is a known effect and ripple timing is typically staggered for different regions to avoid an aggregate "bounce back" effect. More sophisticated load control can overcome this effect [6].

Unmet hot water demand increases with load restrictions. Load control on electric hot water cylinders reduces hot water serviceability by approximately 43% compared with non-load controlled hot water heating. However, electric resistive hot water heating with load control is widely deployed so this level of lost serviceability may not be totally unacceptable.

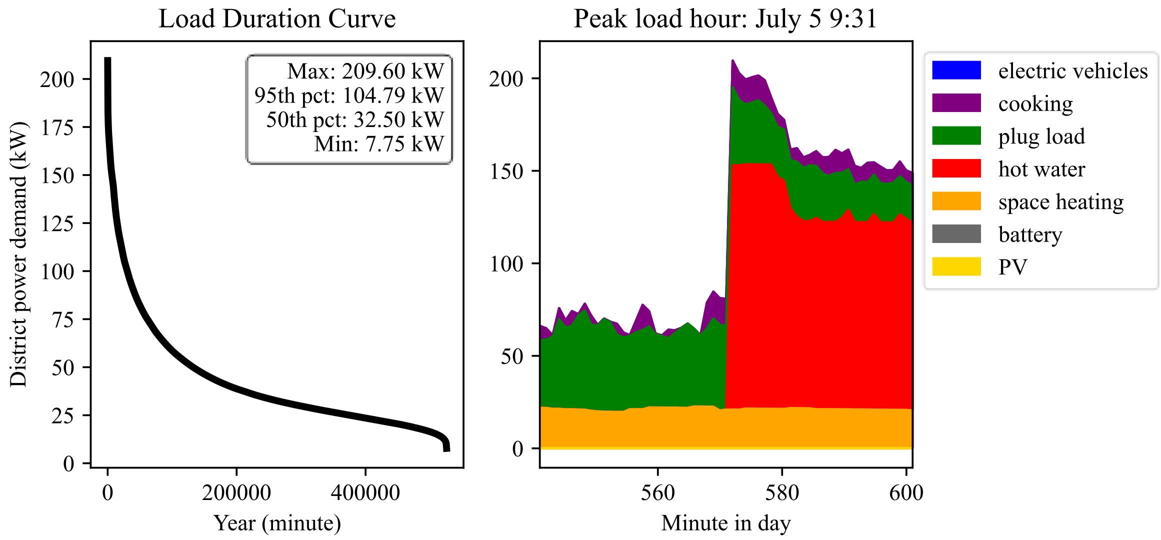

Figure 3-1: Peak load hour and load duration curve for electrification of hot water with load control intervention for a cluster of 60 households at Auckland

Hot water heat pumps significantly reduce electricity consumption (~ -25%) and peak demands (-21% to -28% for 95th pct demand, or -3% to -13% of maximum demand), simply due to increased appliance efficiency. Adding load control reduces peak power loads to between (-12% to -17%, maximum demand) and increases lost hot water serviceability by 30-60% compared with non-load controlled hot water heat pumps.

3.3.3 *Non-electric*

Non-electric interventions, including gas cooking and wood-fuelled space heating, reduce power loads on electricity networks. Results for these interventions are summarised in Table 3-10.

Table 3-10: Relative change from the baseline case for non-electric interventions for a cluster of 60 households in a mixed age neighbourhood at four locations

	INTERVENTION	ELECTRICITY TOTAL (%)	ENERGY TOTAL (%)	CARBON TOTAL (%)	MAX POWER DEMAND (%)	95th PCT POWER DEMAND (%)
Auckland	Wood SH	-8%	10%	-1%	-9%	-11%
	Gas CK	-7%	0%	1%	-6%	-12%
Palmerston North	Wood SH	-8%	11%	-2%	-14%	-11%
	Gas CK	-7%	7%	11%	0%	-11%
Christchurch	Wood SH	-14%	21%	-1%	-21%	-19%
	Gas CK	-7%	1%	3%	-10%	-9%
Dunedin	Wood SH	-12%	17%	-2%	-22%	-17%
	Gas CK	-7%	5%	10%	-12%	-9%

Wood-fuelled space heating reduces electricity consumption (-8 to -14%) and peak power loads (-9% to -22%), but only slightly changes GHG emissions (-1% to 2%). Gas cooking reduces electricity demand (~7%), moderately increases GHG emissions (1-11%), and decreases peak power loads (0% to -12%). Overall, wood-fuelled space heating is a promising way to decrease GHG emissions while significantly reducing peak power demands on electricity networks, particularly for colder regions. Wood-fuelled space heating may be a complementary technology for enabling electrification by mitigating higher electricity energy requirements and peak loads. Gas cooking also reduces peak power loads on the electricity network but with the disadvantage of higher GHG emissions.

3.3.4 *Electric vehicles*

Transport electrification interventions represent a 40% or 100% change of household vehicles to full Electric Vehicles, with a battery capacity of 39 kWh (full technological capacities are described in Table 5-20). Results for EV interventions are summarised in Table 3-11. EV uptake significantly reduces GHG emissions, with reductions varying with location due to differing vehicle ownership and travel demands in the four cities considered in this study. Greatest impacts are seen in Auckland and the least in Dunedin.

A 40% penetration of EVs in the private sector leads to a 10% to 16% increase in electricity consumption, -30% reduction in transportation energy, and -36% reduction in total carbon emissions. A 100% penetration of EV's leads to a 24-42% increase in electricity demand, a -8% decrease in transportation energy, and -72% reduction in total carbon emissions. The relatively high energy efficiency of EVs can be seen in the significant reduction they produce in transportation energy.

Peak power loads are a key concern with EV uptake. Predicted power loads are affected by the stochasticity in the EV model, which makes it difficult to confidently determine the impact of EVs on the electricity network. A 40% EV uptake appears to increase maximum power demand in the network by up to 14% across all locations, and a 100% uptake increases maximum power demand by up to 21%.

Load control of EV charging significantly reduce power demands on the electricity network. Load control restricts charging times, which reduces charging duration availability. However, while load control reduces peak power demands it does not appear to reduce vehicle serviceability.

Table 3-11: Relative change from the baseline case for greater use of electric vehicles for a cluster of 60 households in a mixed age neighbourhood at four locations

	INTERVENTION	ELECTRICITY TRANSPORT (%)	ELECTRICITY TOTAL (%)	ENERGY TRANSPORT (%)	ENERGY TOTAL (%)	CARBON TRANSPORT (%)	CARBON TOTAL (%)	MAX POWER DEMAND (%)	95th PCT POWER DEMAND (%)	UNMET TRAVEL DEMAND/VKL (%)
AUCKLAND	EV 40%	3464%	16%	-30%	-19%	-36%	-28%	14%	8%	139%
	EV 40% w LC	3434%	16%	-31%	-19%	-36%	-28%	6%	9%	61%
	EV 100%	8773%	41%	-78%	-49%	-91%	-72%	21%	18%	133%
	EV 100% w LC	8785%	42%	-78%	-49%	-91%	-72%	5%	13%	144%
PALMERSTON NORTH	EV 40%	3102%	11%	-30%	-14%	-36%	-25%	11%	2%	-28%
	EV 40% w LC	3010%	11%	-31%	-14%	-36%	-25%	0%	-2%	-46%
	EV 100%	7937%	28%	-76%	-36%	-90%	-63%	12%	11%	-9%
	EV 100% w LC	7683%	27%	-77%	-36%	-90%	-63%	9%	4%	-24%
CHRISTCHURCH	EV 40%	3164%	12%	-30%	-16%	-35%	-26%	-3%	2%	-31%
	EV 40% w LC	3118%	12%	-30%	-16%	-35%	-26%	-5%	3%	0%
	EV 100%	8028%	31%	-75%	-40%	-88%	-65%	3%	10%	-6%
	EV 100% w LC	7957%	31%	-75%	-40%	-88%	-65%	1%	6%	13%
DUNEDIN	EV 40%	3249%	10%	-30%	-12%	-35%	-24%	-4%	3%	-9%
	EV 40% w LC	3182%	10%	-30%	-12%	-36%	-24%	-7%	0%	-27%
	EV 100%	8288%	25%	-77%	-32%	-90%	-61%	-2%	6%	-25%
	EV 100% w LC	8133%	24%	-77%	-32%	-91%	-61%	7%	4%	0%

These results are for MUA locations which have lower vehicle ownership and lower daily vehicle travel distance than SUAs and rural areas. Hence, results are expected to increase in magnitude for non MUAs, increasing the efficiency of EVs for emissions reductions but also presenting greater challenges for peak loading on networks.

Overall, EV's are an effective means of emissions and energy reductions, while producing moderate increases in peak loads, which can be mitigated with load control.

3.3.5 *Distributed energy resources*

Distributed Energy Resource (DER) interventions include PVs, domestic batteries, and combinations of the two. DER results are summarised in

Table 3-12, with additional assessments for the proportion of PV generation that is self-consumed, i.e. PV electricity consumed within the BC.

Table 3-12: Relative change from baseline case of distributed energy resource interventions for a cluster of 60 households in mixed age neighbourhoods at four locations

		ELECTRICITY DEMAND (MWh)	PV GEN (MWh)	PV SELF CONS./PV GEN (%)	PV SELF CONS./ ELECTRICITY DEMAND (%)	NON TRANSPORT CARBON EMISSIONS (%)	CARBON EMISSIONS (%)	MAX POWER DEMAND (%)	95th PCT POWER DEMAND (%)	MIN DEMAND (kW)
AUCKLAND	PV 5kWp 40%	350.7	-76.9	95%	21%	-19%	-4%	16%	-7%	-39.1
	PV 5kWp 100%	350.2	-188.3	66%	35%	-46%	-9%	5%	-13%	-110.8
	BT 2.4kWh	350.8	0.0	0%	0%	0%	0%	-3%	0%	7.2
	BT 6.4kWh	350.5	0.0	0%	0%	0%	0%	-4%	-3%	8
	PV 5kWp & BT 6.4 kWh	350.6	-188.3	68%	37%	-46%	-9%	-8%	-16%	-112.3
CHRISTCHURCH	PV 5kWp 40%	376.5	-82.0	93%	20%	-19%	-5%	-5%	-7%	-55.2
	PV 5kWp 100%	376.3	-199.8	64%	34%	-45%	-12%	-6%	-13%	-172.1
	BT 2.4kWh	376.7	0.0	0%	0%	0%	0%	-10%	-2%	7.9
	BT 6.4kWh	376.1	0.0	0%	0%	0%	0%	-9%	-4%	8
	PV 5kWp & BT 6.4 kWh	376.3	-199.8	66%	35%	-45%	-12%	-1%	-15%	-163.6
DUNEDIN	PV 5kWp 40%	366.8	-83.4	91%	21%	-18%	-6%	4%	-5%	-53.3
	PV 5kWp 100%	367.0	-203.5	62%	34%	-44%	-14%	3%	-13%	-168.5
	BT 2.4kWh	367.2	0.0	0%	0%	0%	0%	-11%	-4%	7.5
	BT 6.4kWh	367.0	0.0	0%	0%	0%	0%	-7%	-4%	7.9
	PV 5kWp & BT 6.4 kWh	367.3	-203.5	64%	36%	-44%	-14%	-10%	-16%	-163.9
PALMERSTON NORTH	PV 5kWp 40%	351.4	-77.6	93%	21%	-18%	-5%	0%	-8%	-47.5
	PV 5kWp 100%	350.7	-190.4	63%	34%	-44%	-13%	-2%	-13%	-136.6
	BT 2.4kWh	351.4	0.0	0%	0%	0%	0%	2%	-3%	7.9
	BT 6.4kWh	350.7	0.0	0%	0%	0%	0%	-2%	-3%	7.1
	PV 5kWp & BT 6.4 kWh	351.2	-190.4	66%	36%	-44%	-13%	-13%	-16%	-128.5

Two levels of Solar PV penetration were assessed - 40% and 100% of households equipped with a 5kWp solar PV array. Both levels of uptake result in significant distributed electricity generation, equal to ~22% and ~54% of electricity demand respectively. However, not all PV electricity generated is consumed within the cluster of households, 91-95% and 62-66% of PV electricity generated is self-consumed for the 40% and 100% cases respectively, demonstrating a saturation effect with the percentage of self-consumed PV generation reducing with higher PV uptake.

In addition to energy production, PV generation leads to small to moderate reductions in peak power demands, with ~-6% and -13% reduction for 95th percentile peak demand for 40% and 100% uptake respectively. Solar PV significantly reduces non-transport GHG emissions by ~-19% and ~-45% for the 40% and 100% case respectively, demonstrating a significant reduction in household emissions are possible with onsite PV electricity production.

The minimum demand demonstrates a notable feature of PV generation. The negative minimum power demand indicates reverse power flow, meaning the cluster is net exporting power at a significant rate. Negative power flows can create issues, such as voltage regulation difficulties on electricity networks, and can affect the longevity of electricity distribution infrastructure. Also, negative power flows can be significant and exceed transformer limits. So, both maximum electricity demand and maximum exported electricity can potentially introduce challenges for local electricity infrastructure. These technical challenges should be considered when considering PVs benefits.

Batteries provide modest decreases in peak loading with reductions in maximum demand between 0 to -4% (95th pct) for the 2.4kWh case and -3% to -4% (95th pct) for the 6.4kWh case. Increasing battery capacity appears to have little additional impact on peak power load reduction, for the battery capacities analysed. In this study, batteries aim to reduce household peaks and receive no feedback from the transformer. Households may all reduce their peak, which can occur at different times, however the transformer peak may experience less significant reductions in peak load due to the diversification among the households.

The peak power shaving mechanism of batteries can be seen in Figure 3-3. This intervention utilises a battery control logic that reduces household power demand independently of other households. Greater reductions can potentially be achieved if household batteries are controlled as a group.

Coupling batteries and PV marginally enhances the level of self-consumed PV electricity by an additional 2-3% and enhances peak load reductions to -1 to -13% of maximum demand.

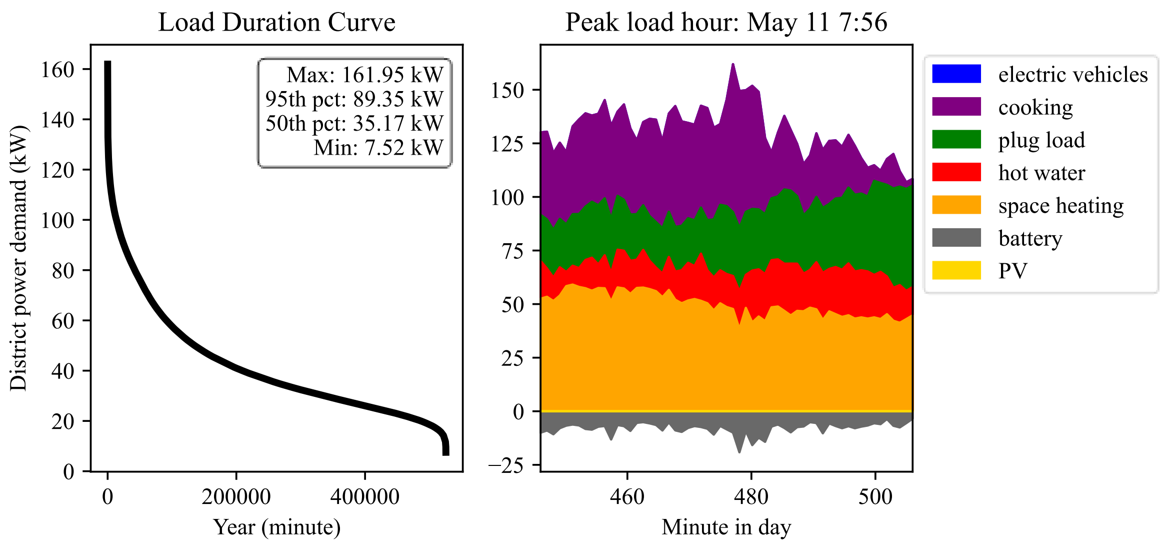

Figure 3-2: LDC and peak load hour for 2.4kWh battery in Dunedin

DER interventions present a means for GHG emission reductions, although the extent of reductions are limited due to an already low emissions factor for New Zealand's network electricity. Batteries and battery-PV combination also present a means for moderate peak demand reductions, with greater reductions potentially achievable with coordinated battery control systems.

3.3.6 *Summary of intervention results*

Building efficiency

- Building efficiency interventions are best targeted to older aged districts and colder climates.
- Improved insulation has only small impacts on electricity consumption and operating GHG emissions but may also reduce peak loads where electric heating is ubiquitous.
- Space heating electrification can moderately increase electricity consumption and peak demands, where heat pumps uptake is low.
- The takeback effect for space heating is significant and should be considered for interventions, particularly for electrification and the impact on peak loads.

Electrification

- Electrification of cooking leads to small increases in electricity demand and peak loads, however the impact will be more significant in locations with high gas cooking penetration.
- Electrification of hot water leads to moderate increase in electricity demand and significant increases in peak load. Hot water load control using simple time-based restrictions can lead to increased peak loading due to "bounce back" effects.
- Hot water heat pumps lead to significant reductions in electricity demand, energy consumption, operating GHG emissions, and peak loading, thus presents an opportunity to reduce emissions with positive network outcomes.

Non-electrification

- Gas cooking presents an opportunity for small to moderate reductions in electricity demand and peak loads, at the cost of similar increases in operating GHG emissions.
- Wood-fuelled space heating presents promising method for small reductions in operating GHG emissions while significantly reducing electricity demand and peak loads.

Electric vehicles

- EVs had the most significant impact on operating GHG emissions of any of the interventions assessed.
- EVs lead to significant increases in electricity demand and moderate increases in peak loads. However, peak loads were largely reduced with load control which had negligible impact on serviceability. This indicates load control will not lead to notable missed travel.
- These EV results are for main urban areas, which have the lowest vehicle ownership and travel distance. Secondary urban and rural areas will have significantly different results (increased electricity demands and peak loading) and hence care should be taken to extrapolate these results to those locations.

Distributed energy resources

- PV demonstrated significant levels of self-consumption within the building cluster, however self-consumption saturates with increasing uptake.
- PV uptake leads to significant reductions of operating GHG emissions.
- PV can produce significant negative peak loads form solar export, and can even exceed peak loading from electricity demands.
- Domestic batteries can lead to moderate reductions in peak loads, with no additional benefit coming from increasing energy storage capacity. Peak load reduction potential is expected to increase where control logic integrates signals such as LV transformer load.
- Coupling PV and batteries marginally increases self-consumption of PV generation and decreases peak loads below what PV and batteries can achieve alone.

3.4 Discussion of pathways results

Three pathways, described in Section 2.4, are assessed. The first pathway (WDSHwEle) includes full electrification of household loads, except for space heating which is provided by wood-stoves, and domestic hot water is provided by hot water heat pumps, and full-electrification of transport; the second pathway (FullE) involves electrification of household loads and transport; and the third pathway (FullEwDER) combines full electrification of household loads and transport with the addition of solar PV and domestic batteries. The relative results for the pathways are included Table 3-13 and absolute results in Appendix Section 5.1

The three pathways produce similar reductions in operating GHG emissions ranging between -72 to -89%, with the magnitude of reductions varying with location. The "FullEwDER" pathway reduces emissions an additional -9 to -15% beyond other pathways, from reduced non-transport emissions.

The wood space heating pathway (WDSHwEle) reduces electricity demand in three locations, with the magnitude of reduction increasing in colder climates, while the other two pathways increase electricity demand. The wood space heating pathway reduces peak power demand by -8% to -21% (-10% mean reduction).

Full electrification (FullE) produces a small to moderate increase of electricity demand (+5% to +16%) and a small decrease or moderate increase peak power demand (-4 to +12%). The addition of DERs (FullEwDER) maintains the increased electricity demand, however 31-33% of demands were met by PV generation within the cluster, leading to a decreased need for electricity from the network. The addition of DER also leads to a net reduction in peak power demand on the network (-7% to -17%, 95^{th} pct).

Overall, the three pathways demonstrate that significant reductions in energy and operating GHG emissions can be achieved through the application of several key technologies with either small additions to peak load or with significant reductions in peak loads. Wood heating, hot water heat pumps, electric vehicles, and the application of load control all can play a significant role in decarbonisation.

Table 3-13: Relative results for pathways

	PATHWAY	ELECTRICITY TRANSPORT %	ELECTRICITY NON-TRANSPORT %	ELECTRICITY TOTAL %	PV SELF CONS/PV GEN %	PV SELF CONS/E DEMAND %	ENERGY TRANSPORT %	ENERGY NON-TRANSPORT %	ENERGY TOTAL %	CARBON TRANSPORT %	CARBON NON-TRANSPORT %	CARBON TOTAL %	MAX POWER DEMAND %	95t[h] PCT POWER DEMAND %	MIN DEMAND (MW)
AUCKLAND	FullE	8753%	-25%	16%			-78%	-32%	-61%	-91%	-36%	-80%	3%	-2%	8.3
	FullEwDER	8766%	-26%	16%	-69%	32%	-78%	-32%	-61%	-91%	-82%	-89%	-5%	-7%	-111.8
	WDSHwEle	8798%	-33%	9%			-78%	-2%	-50%	-91%	-36%	-80%	-8%	-8%	7.6
PALMERSTON NORTH	FullE	7661%	-22%	5%			-77%	-41%	-58%	-90%	-36%	-74%	12%	-9%	8.3
	FullEwDER	7697%	-22%	5%	-63%	33%	-77%	-41%	-58%	-90%	-81%	-88%	-3%	-17%	-136.7
	WDSHwEle	7733%	-33%	-6%			-77%	-3%	-38%	-90%	-37%	-74%	-10%	-23%	7.5
CHRISTCHURCH	FullE	7886%	-23%	8%			-75%	-35%	-57%	-88%	-34%	-74%	-4%	-9%	8.6
	FullEwDER	7967%	-23%	8%	-63%	31%	-75%	-35%	-57%	-88%	-80%	-86%	-10%	-15%	-170.7
	WDSHwEle	7921%	-38%	-7%			-75%	21%	-31%	-88%	-35%	-74%	-21%	-24%	7.8
DUNEDIN	FullE	8168%	-17%	7%			-77%	-46%	-59%	-91%	-34%	-72%	-1%	-5%	8.5
	FullEwDER	8071%	-17%	7%	-60%	31%	-77%	-46%	-59%	-91%	-79%	-87%	-6%	-14%	-170.3
	WDSHwEle	8132%	-36%	-12%			-77%	9%	-27%	-91%	-35%	-72%	-16%	-29%	7.5

4. Conclusions

This report assesses a range of interventions and pathways for reducing operating GHG emissions from New Zealand's homes and urban areas, by using an Urban Energy Model (UEM) to simulate the annual energy performance of a cluster of 60 households connected to a single low voltage transformer. The domains of the UEM include space heating, cooking, plug loads, electric vehicles, solar PV, and batteries.

The main results of the simulation analysis are presented in this report, including cumulative annual energy demand, electricity demand, and operating GHG emissions, and peak power demand metrics. The results provide a basis for comparing the relative benefits and costs of different decarbonisation interventions and pathways; however, a full cost benefit analysis of these actions is not considered in this report. The economics of the DEEDs and the effects of embodied GHG emissions are not assessed here.

In total, 20 interventions and 3 pathways are assessed. The results provide insights into the effectiveness of these 'DEEDs' strategies, identifying interventions which are most effective and pathways that reduce operating GHG emissions without overloading electricity networks.

4.1 Key takeaways

Several technologies are identified as playing a significant role in decarbonisation of households including wood heating, hot water heat pumps, electric vehicles, and the application of smart load control.

- Hot water heat pumps lead to significant reductions in electricity demand, energy consumption, operating GHG emissions, and peak loads, so is a promising technology for reducing emissions without overloading electricity networks.
- Wood-fuelled space heating can provide small reductions in operating GHG emissions but, importantly, they reduce electricity demand and peak power loads on the electricity network. Wood heating increases the capacity of the network to support electrification of private transport and other power intensive interventions.
- EVs can significantly reduce operating GHG emissions due to the large portion of household emissions arising from transportation. EV's also lead to significant increases in electricity demand and moderate increases in peak power loads, creating a significant impact on the electricity network. However, it appears peak loads on the grid can largely be managed with smart control of EV charging and other building-related electricity loads, without compromising the ability of EVs to meet private travel demands.
- Rooftop PV electricity generation can lead to significant reductions in operating GHG emissions, and significant portions of this generation can be consumed within the local network. However, PV generation can produce high negative peak loads resulting in technical challenges at high levels of penetration, such as voltage regulation on the electricity network.

More broadly, a range of results were obtained for the interventions assessed.

- Building energy efficiency interventions are best targeted to older aged districts and colder climates.
- Improved insulation has relatively small impacts on electricity consumption and operating GHG emissions but may reduce peak power loads on the network where electric heating is ubiquitous.
- The takeback effect for space heating can significantly offset the operating GHG emissions reductions of interventions. Therefore, takeback should be considered when forecasting the impacts of space heating electrification and improvements in building energy efficiency on GHG emissions from households.

Three pathways assessed possible combinations of technologies. The pathways demonstrate that significant reductions in energy and GHG emissions can be achieved through strategic combinations of technologies without increasing peak loads on the electricity network.

4.2 Limitations

The work has several limitations. The scope of analysis was necessarily limited to existing technologies and selected levels of uptake of the technologies assessed. For example, only 40% and 100% uptake of 5kWp solar PV arrays were tested. Different levels of uptake may produce better results. However, this report established the technologies and combinations of technologies of most future interest for a more targeted analysis.

Data limitations required the use of simplifying assumptions. For example, a lack of detailed regional housing data required the current use of building energy technologies to be based on national data. For example, the proportion of gas hot water heating used a national average figure for all regions but is likely more concentrated in some regions.

Household time of use energy data was also limited. So, this study created a range of power time of use profiles from the Green Grid Study, which monitored the electricity circuits of a limited number of households. More household data on occupant behaviour would enable better power time of use profiles to be created, better capturing the diversity of behaviour, and increasing the accuracy of the Urban Energy Model.

Embodied emissions were also out of scope for this analysis, which can be significant for many of the most promising technologies (EVs, Batteries, and Solar PV). Including embodied emissions would in all cases increase the total emissions, however it is the most comprehensive means to compare technologies. While limited to operating emissions, this report highlights the technologies which are most suitable for further analysis and will complement future analyses that include embodied emissions.

A constant emissions intensity was used in this report, however emissions intensity for network electricity changes with time. It is commonly thought that the emissions intensity correlates highly with peak load, i.e. that peak times have the highest emissions intensity, and hence that peak load reductions in this report are correlated with higher emissions reductions. However, the relationship between load and power system emissions is more complicated and it is not always true that peak times experience the highest emissions intensity [7]. This is in-part due to the role of hydropower for load following and meeting peak demands in the New Zealand power system. To fully understand the impact of demand reductions on power system emissions, an appropriate power systems dispatch model should be employed and coupled to the UEM.

5. Appendices

5.1 Absolute results

Table 5-1: Absolute results for energy interventions on a cluster of 60 households in a mixed age neighbourhood at Auckland

INTERVENTION	ELECTRICITY TRANSPORT (MWh)	ELECTRICITY TOTAL (MWh)	PV GEN (MWh)	PV EXP (MWh)	PV SELF CONS (MWh)	ENERGY TRANSPORT (MWh)	ENERGY TOTAL (MWh)	CARBON TRANSPORT (T)	CARBON TOTAL (T)	MAX POWER DEMAND (kW)	95th PCT POWER DEMAND (kW)	MIN POWER DEMAND (kW)
Baseline	1.7	349.3	0.0	0.0	0.0	654.8	1036.4	162.8	204.3	163.8	85.7	8.5
Insulation	1.5	344.4	0.0	0.0	0.0	654.7	1024.6	162.8	202.9	160.5	84.7	8.0
HPSH	1.7	346.9	0.0	0.0	0.0	654.8	1023.1	162.8	202.7	172.9	88.2	7.5
Insulation & HPSH	1.4	342.7	0.0	0.0	0.0	654.6	1018.9	162.8	202.3	163.3	82.8	7.8
Ele CK	1.8	351.5	0.0	0.0	0.0	655.0	1036.3	162.8	204.1	167.0	87.6	8.1
Ele HW	1.8	374.0	0.0	0.0	0.0	654.9	1040.4	162.8	202.8	186.2	93.2	7.2
Ele HW w LC	1.7	371.6	0.0	0.0	0.0	654.9	1038.0	162.8	202.6	209.6	104.8	7.8
HPHW	1.5	261.2	0.0	0.0	0.0	654.7	927.6	162.8	191.3	149.8	62.0	8.2
HPHW w LC	1.6	260.8	0.0	0.0	0.0	654.7	927.2	162.8	191.2	143.8	66.1	8.3
Wood SH	1.6	322.6	0.0	0.0	0.0	654.7	1141.4	162.8	202.8	148.4	76.4	8.3
Gas CK	1.6	323.4	0.0	0.0	0.0	654.8	1036.2	162.8	206.7	154.1	75.4	8.5
Idealistic heating	1.7	361.2	0.0	0.0	0.0	654.8	1074.7	162.8	206.1	171.3	89.9	8.2
EV 40%	58.9	406.7	0.0	0.0	0.0	455.2	837.0	104.7	146.3	186.4	92.1	10.9
EV 40% w LC	58.4	405.8	0.0	0.0	0.0	454.7	836.0	104.7	146.2	174.1	93.0	9.3
EV 100%	146.7	494.1	0.0	0.0	0.0	146.7	528.1	15.1	56.6	198.5	101.2	8.9
EV 100% w LC	146.9	494.8	0.0	0.0	0.0	146.9	528.8	15.1	56.7	172.1	97.1	7.1
PV 5kWp 40%	1.7	349.3	-76.9	-3.9	73.0	654.9	1036.4	162.8	196.4	189.7	79.4	-39.1
PV 5kWp 100%	1.4	348.8	-188.3	-64.6	123.7	654.6	1035.9	162.8	184.9	172.0	74.5	-110.8
BT 2.4kWh	1.6	349.4	0.0	0.0	0.0	654.8	1036.6	162.8	204.3	159.3	85.4	7.2
BT 6.4kWh	1.7	349.1	0.0	0.0	0.0	654.9	1036.2	162.8	204.3	157.9	82.7	8.0
PV 5kWp & BT 6.4 kWh	1.4	349.2	-188.3	-60.0	128.3	654.6	1036.3	162.8	185.0	150.1	71.9	-112.3

Table 5-2: Absolute results for energy interventions on a cluster of 60 households in a mixed age neighbourhood at Palmerston North

INTERVENTION	ELECTRICITY TRANSPORT (MWh)	ELECTRICITY TOTAL (MWh)	PV GEN (MWh)	PV EXP (MWh)	PV SELF CONS (MWh)	ENERGY TRANSPORT (MWh)	ENERGY TOTAL (MWh)	CARBON TRANSPORT (T)	CARBON TOTAL (T)	MAX POWER DEMAND (kW)	95th PCT POWER DEMAND (kW)	MIN POWER DEMAND (kW)
Baseline	1.2	351.5	0.0	0.0	0.0	413.3	877.7	102.7	147.0	165.8	87.2	8.1
Insulation	1.3	345.5	0.0	0.0	0.0	413.4	850.6	102.7	145.0	171.7	84.6	8.2
HPSH	1.1	361.9	0.0	0.0	0.0	413.2	797.1	102.7	144.3	173.1	90.4	7.2
Insulation & HPSH	1.2	353.1	0.0	0.0	0.0	413.3	788.3	102.7	143.4	188.1	87.1	8.2
Ele CK	1.2	353.5	0.0	0.0	0.0	413.3	877.4	102.7	146.8	166.1	88.3	8.1
Ele HW	1.1	375.4	0.0	0.0	0.0	413.2	901.6	102.7	149.5	175.6	93.6	8.0
Ele HW w LC	1.3	374.3	0.0	0.0	0.0	413.4	900.5	102.7	149.4	208.9	100.6	8.4
HPHW	1.1	262.4	0.0	0.0	0.0	413.2	788.6	102.7	137.9	160.3	67.8	7.6
HPHW w LC	1.2	262.5	0.0	0.0	0.0	413.3	788.7	102.7	137.9	140.7	68.2	8.1
Wood SH	1.2	321.7	0.0	0.0	0.0	413.3	973.0	102.7	144.0	143.3	77.3	7.6
Gas CK	1.2	325.3	0.0	0.0	0.0	471.4	935.3	117.2	163.8	165.9	77.3	8.4
Idealistic heating	1.3	358.4	0.0	0.0	0.0	413.4	970.6	102.7	155.3	180.5	90.3	8.1
EV 40%	39.2	389.4	0.0	0.0	0.0	287.5	751.8	65.9	110.1	183.7	89.0	10.1
EV 40% w LC	38.1	388.3	0.0	0.0	0.0	286.4	750.7	65.7	110.0	165.6	85.8	8.7
EV 100%	98.5	448.3	0.0	0.0	0.0	98.5	562.4	10.1	54.4	186.3	97.2	8.9
EV 100% w LC	95.3	445.2	0.0	0.0	0.0	95.3	559.3	9.8	54.1	180.6	91.1	8.2
PV 5kWp 40%	1.3	351.4	-77.6	-5.4	72.2	413.4	877.6	102.7	139.0	166.0	80.2	-47.5
PV 5kWp 100%	1.2	350.7	-190.4	-70.0	120.4	413.3	876.9	102.7	127.4	161.7	75.8	-136.6
BT 2.4kWh	1.3	351.4	0.0	0.0	0.0	413.4	877.6	102.7	147.0	168.9	84.2	7.9
BT 6.4kWh	1.1	350.7	0.0	0.0	0.0	413.2	877.0	102.7	147.0	162.2	84.2	7.1
PV 5kWp & BT 6.4 kWh	1.3	351.2	-190.4	-65.3	125.2	413.4	877.4	102.7	127.4	143.7	72.9	-128.5

Table 5-3: Absolute results for energy interventions on a cluster of 60 households in a mixed age neighbourhood at Christchurch

INTERVENTION	ELECTRICITY TRANSPORT (MWh)	ELECTRICITY TOTAL (MWh)	PV GEN (MWh)	PV EXP (MWh)	PV SELF CONS (MWh)	ENERGY TRANSPORT (MWh)	ENERGY TOTAL (MWh)	CARBON TRANSPORT (T)	CARBON TOTAL (T)	MAX POWER DEMAND (kW)	95th PCT POWER DEMAND (kW)	MIN POWER DEMAND (kW)
Baseline	1.5	376.4	0.0	0.0	0.0	516.4	962.5	128.3	173.7	190.5	94.9	8.3
Insulation	1.4	364.3	0.0	0.0	0.0	516.3	935.5	128.3	171.6	175.6	91.5	7.3
HPSH	1.4	378.4	0.0	0.0	0.0	516.3	916.4	128.3	171.6	175.0	96.3	7.4
Insulation & HPSH	1.4	365.4	0.0	0.0	0.0	516.3	903.4	128.3	170.2	164.3	90.7	7.7
Ele CK	1.2	378.2	0.0	0.0	0.0	516.1	962.0	128.3	173.5	198.4	97.2	8.0
Ele HW	1.4	401.1	0.0	0.0	0.0	516.3	987.2	128.3	176.3	186.6	102.2	8.3
Ele HW w LC	1.5	399.2	0.0	0.0	0.0	516.4	985.3	128.3	176.1	209.9	106.6	8.5
HPHW	1.3	288.2	0.0	0.0	0.0	516.2	874.3	128.3	164.7	165.7	74.0	8.4
HPHW w LC	1.4	287.7	0.0	0.0	0.0	516.3	873.8	128.3	164.6	162.3	75.6	8.6
Wood SH	1.4	322.4	0.0	0.0	0.0	516.3	1165.5	128.3	171.2	150.9	76.5	8.3
Gas CK	1.2	350.4	0.0	0.0	0.0	528.0	974.1	131.3	179.0	170.7	86.1	8.5
Idealistic heating	1.3	405.2	0.0	0.0	0.0	516.2	1030.2	128.3	177.9	212.5	106.0	8.3
EV 40%	47.4	422.5	0.0	0.0	0.0	361.1	807.4	83.0	128.4	185.7	96.7	9.3
EV 40% w LC	46.7	421.8	0.0	0.0	0.0	360.4	806.7	82.9	128.3	181.9	97.4	8.4
EV 100%	118.0	492.8	0.0	0.0	0.0	129.8	575.8	15.1	60.4	196.6	104.4	11.0
EV 100% w LC	117.0	492.0	0.0	0.0	0.0	128.8	575.0	15.0	60.4	192.2	100.5	8.6
PV 5kWp 40%	1.5	376.5	-82.0	-6.0	76.0	516.4	962.6	128.3	165.3	181.0	88.0	-55.2
PV 5kWp 100%	1.3	376.3	-199.8	-72.3	127.5	516.2	962.4	128.3	153.2	178.5	83.0	-172.1
BT 2.4kWh	1.3	376.7	0.0	0.0	0.0	516.3	962.8	128.3	173.8	171.5	92.7	7.9
BT 6.4kWh	1.4	376.1	0.0	0.0	0.0	516.3	962.2	128.3	173.7	174.0	91.6	8.0
PV 5kWp & BT 6.4 kWh	1.4	376.3	-199.8	-67.7	132.1	516.3	962.4	128.3	153.2	188.8	81.0	-163.6

Table 5-4: Absolute results for energy interventions on a cluster of 60 households in a mixed age neighbourhood at Dunedin

INTERVENTION	ELECTRICITY TRANSPORT (MWh)	ELECTRICITY TOTAL (MWh)	PV GEN (MWh)	PV EXP (MWh)	PV SELF CONS (MWh)	ENERGY TRANSPORT (MWh)	ENERGY TOTAL (MWh)	CARBON TRANSPORT (T)	CARBON TOTAL (T)	MAX POWER DEMAND (kW)	95th PCT POWER DEMAND (kW)	MIN POWER DEMAND (kW)
Baseline	1.1	367.1	0.0	0.0	0.0	392.9	954.4	97.7	145.0	181.9	92.6	8.4
Insulation	1.0	355.6	0.0	0.0	0.0	392.9	904.3	97.7	142.2	166.8	88.0	8.0
HPSH	1.3	391.5	0.0	0.0	0.0	393.1	806.4	97.7	142.3	192.2	100.3	7.6
Insulation & HPSH	1.0	374.3	0.0	0.0	0.0	392.8	789.2	97.7	140.5	165.7	93.9	7.6
Ele CK	1.2	369.6	0.0	0.0	0.0	393.0	954.7	97.7	144.8	176.1	93.8	8.0
Ele HW	1.1	391.9	0.0	0.0	0.0	393.0	979.3	97.7	147.6	189.1	97.4	7.7
Ele HW w LC	1.3	390.3	0.0	0.0	0.0	393.1	977.6	97.7	147.4	219.2	107.4	8.6
HPHW	1.2	279.1	0.0	0.0	0.0	393.0	866.5	97.7	136.0	165.9	73.4	7.9
HPHW w LC	1.1	278.7	0.0	0.0	0.0	392.9	866.0	97.7	136.0	151.0	73.5	8.0
Wood SH	1.3	322.5	0.0	0.0	0.0	393.1	1112.8	97.7	141.8	142.8	76.8	7.9
Gas CK	1.2	341.4	0.0	0.0	0.0	442.6	1004.1	110.0	159.7	159.8	83.9	7.4
Idealistic heating	1.2	391.8	0.0	0.0	0.0	393.0	1071.2	97.7	150.1	179.8	99.2	7.3
EV 40%	36.5	402.4	0.0	0.0	0.0	274.6	836.0	63.0	110.4	175.2	95.0	9.5
EV 40% w LC	35.8	401.9	0.0	0.0	0.0	273.9	835.5	63.0	110.3	169.5	92.8	7.5
EV 100%	91.5	457.3	0.0	0.0	0.0	91.5	652.8	9.4	56.8	178.4	98.5	10.8
EV 100% w LC	89.8	455.4	0.0	0.0	0.0	89.8	650.9	9.2	56.6	194.0	96.2	8.3
PV 5kWp 40%	0.9	366.8	-83.4	-7.3	76.1	392.8	954.1	97.6	136.4	188.5	88.1	-53.3
PV 5kWp 100%	1.2	367.0	-203.5	-77.1	126.4	393.1	954.3	97.7	124.1	188.0	80.5	-168.5
BT 2.4kWh	1.0	367.2	0.0	0.0	0.0	392.9	954.5	97.7	145.0	162.0	89.4	7.5
BT 6.4kWh	1.1	367.0	0.0	0.0	0.0	393.0	954.4	97.7	145.0	168.9	89.2	7.9
PV 5kWp & BT 6.4 kWh	1.2	367.3	-203.5	-72.8	130.7	393.1	954.6	97.7	124.1	163.3	77.4	-163.9

Table 5-5: Absolute results for pathways

	PATHWAY	ELECTRICITY TRANSPORT MWh	ELECTRICITY TOTAL MWh	PV GEN MWh	PV EXP MWh	PV SELF CONS MWh	ENERGY TRANSPORT MWh	ENERGY TOTAL MWh	CARBON TRANSPORT T	CARBON TOTAL T	MAX POWER DEMAND kW	95^{th} PCT POWER DEMAND kW	MIN DEMAND kW	UNMET HW DEMAND L.m/hh	UNMET TRANSPORTATION DEMAND km/vkl
AUCKLAND	Baseline	1.7	350.7	0.0	0.0	0.0	654.8	1037.8	162.8	204.5	163.8	85.7	8.5	-4158.3	225.4
	FullE	146.4	406.6	0.0	0.0	0.0	146.4	406.6	15.0	41.8	168.0	84.1	8.3	-10044.5	509.1
	FullEwDER	146.6	405.9	-188.3	-58.3	130.0	146.6	405.9	15.1	22.4	155.6	79.3	-111.8	-16568.8	509.4
	WDSHwEle	147.1	380.9	0.0	0.0	0.0	147.1	523.5	15.1	41.7	151.1	78.6	7.6	-10204.4	402.3
PALMERSTON NORTH	Baseline	1.2	351.5	0.0	0.0	0.0	413.3	877.7	102.7	147.0	165.8	87.2	8.1	-4163.2	0.0
	FullE	95.1	368.8	0.0	0.0	0.0	95.1	368.8	9.8	37.9	185.4	79.4	8.3	-10072.1	135.7
	FullEwDER	95.5	368.4	-190.4	-70.6	119.8	95.5	368.4	9.8	18.3	161.2	72.7	-136.7	-16441.5	197.1
	WDSHwEle	95.9	329.7	0.0	0.0	0.0	95.9	545.9	9.9	37.7	148.4	67.3	7.5	-10076.8	166.7
CHRISTCHURCH	Baseline	1.5	376.4	0.0	0.0	0.0	516.4	962.5	128.3	173.7	190.5	94.9	8.3	-4110.7	60.2
	FullE	115.9	405.8	0.0	0.0	0.0	127.7	417.6	14.9	44.6	183.8	86.6	8.6	-10162.3	211.8
	FullEwDER	117.1	405.7	-199.8	-74.3	125.5	128.9	417.5	15.0	24.1	170.6	80.5	-170.7	-16565.6	207.0
	WDSHwEle	116.4	350.7	0.0	0.0	0.0	128.3	667.6	14.9	44.4	149.7	72.2	7.8	-10203.3	241.7
DUNEDIN	Baseline	1.1	367.1	0.0	0.0	0.0	392.9	954.4	97.7	145.0	181.9	92.6	8.4	-4024.7	25.6
	FullE	90.2	393.3	0.0	0.0	0.0	90.2	393.3	9.3	40.4	180.0	88.4	8.5	-10036.6	242.2
	FullEwDER	89.2	391.3	-203.5	-80.5	123.0	89.2	391.3	9.2	19.3	171.3	79.7	-170.3	-16379.7	146.7
	WDSHwEle	89.8	323.9	0.0	0.0	0.0	89.8	699.4	9.2	39.9	152.0	66.1	7.5	-10074.6	198.5

5.2 Building cluster input files for the baseline scenario

The building cluster inputs for the baseline 'mixed age' neighbourhoods are included in Table 5-6. The 'old' and 'new' neighbourhoods are identical to the 'mixed age' neighbourhood, except for insulation levels applied to the model homes.

Table 5-6: Baseline building cluster for the mixed age district

HOUSEHOLD	TYPICAL BUILDING MODEL	WALL TYPE	DECADE BUILT (MIXED)	UPGRADED	INSULATION	HEATING EQUIP (AUK)	HEATING EQUIP (PN)	HEATING EQUIP (CAN)	HEATING EQUIP (DUN)	HWC VOLUME (L)	DHW DEMAND (L/DAY)	VEHICLE OWNERSHIP (AUK)	VEHICLE OWNERSHIP (CHC)	VEHICLE OWNERSHIP (PN)	VEHICLE OWNERSHIP (DUN)	EVs	HWC FUEL	RIPPLE	COOKING FUEL	HEATING BEHAVIOUR
1	A	Concrete	2010-2019	Original	N3	W	G	HP+E	HP+E	100	50	0	0	0	0	0	Electric	No ripple	Elec	Underheated
2	A	Concrete	1970-1979	Original	N1	HP+E	HP+W	W+E	HP+W	100	50	0	0	0	0	0	Electric	Ripple	Gas	Underheated
3	A	Weatherboard	<1969	Original	N1	HP+E	HP+W	HP+W	HP+W	100	100	1	1	1	1	1	Gas	No ripple	Elec	Realistic
4	A	Sheet cladding	<1969	Original	N1	HP	W	HP	W	100	150	2	2	1	1	0	Electric	No ripple	Elec	Idealistic
5	B	Brick	<1969	Upgraded	N2	HP+E	HP+W	HP+W	HP+W	100	50	0	0	0	0	0	Electric	No ripple	Gas	Underheated
6	B	Concrete	<1969	Upgraded	N2	HP	G	HP	G	100	50	0	0	0	0	0	Gas	No ripple	Elec	Idealistic
7	B	Weatherboard	1970-1979	Original	N1	HP	W	HP	W	100	50	1	1	0	0	0	Electric	Ripple	Elec	Realistic
8	B	Brick	1980-1989	Original	N1	HP+E	HP+E	HP+W	HP+W	100	100	1	1	1	1	0	Electric	No ripple	Elec	Underheated
9	C	Sheet cladding	<1969	Original	N1	HP	G	HP	HP+E	100	100	1	1	1	1	0	Gas	No ripple	Elec	Realistic
10	C	Concrete	<1969	Original	N1	HP	W	HP	G	100	100	1	1	1	1	0	Electric	No ripple	Elec	Idealistic
11	C	Weatherboard	<1969	Upgraded	N2	W	G	G	HP+E	100	100	1	1	1	1	0	Electric	Ripple	Elec	Realistic
12	C	Concrete	1980-1989	Original	N1	HP+E	HP+E	HP+E	HP+E	100	100	1	1	1	1	0	Electric	Ripple	Elec	Idealistic
13	D	Weatherboard	1970-1979	Original	N1	HP+E	HP+W	W+E	HP+W	100	150	2	2	1	1	0	Electric	Ripple	Elec	Idealistic
14	D	Brick	2000-2009	Upgraded	N3	G	HP+E	HP+E	HP+E	100	150	2	2	1	2	0	Electric	No ripple	Elec	Realistic
15	D	Concrete	<1969	Original	N1	G	HP+E	HP+E	HP+E	100	200	2	2	2	2	0	Electric	Ripple	Elec	Realistic
16	D	Concrete	<1969	Original	N1	G	HP+E	HP+E	HP+E	100	250	3	3	2	3	0	Electric	No ripple	Elec	Idealistic
17	E	Brick	<1969	Original	N1	HP	W	HP	W	150	50	1	1	0	0	0	Electric	Ripple	Elec	Idealistic
18	E	Weatherboard	<1969	Original	N1	HP+E	HP+W	W+E	HP+W	150	50	1	1	1	0	0	Electric	Ripple	Elec	Underheated
19	E	Sheet cladding	<1969	Upgraded	N2	W	G	G	HP+E	150	50	1	1	1	0	0	Electric	Ripple	Elec	Underheated
20	E	Sheet cladding	1970-1979	Upgraded	N2	G	HP+E	HP+E	HP+E	150	50	1	1	1	1	0	Electric	No ripple	Elec	Realistic
21	E	Brick	2010-2019	Original	N3	G	HP+E	HP+E	HP+E	150	50	1	1	1	1	0	Gas	No ripple	Elec	Idealistic
22	E	Concrete	1990-1999	Original	N3	HP+E	HP+E	HP+W	HP+W	150	50	1	1	1	1	0	Electric	Ripple	Elec	Idealistic
23	F	Sheet cladding	<1969	Original	N1	W	G	HP+E	HP+E	150	50	1	1	1	1	0	Electric	Ripple	Elec	Underheated
24	F	Weatherboard	<1969	Upgraded	N2	HP+E	HP+W	HP+W	HP+W	150	50	1	1	1	1	0	Gas	No ripple	Elec	Underheated
25	F	Concrete	2010-2019	Upgraded	N3	HP	W	HP	W	150	100	1	1	1	1	0	Electric	No ripple	Elec	Realistic
26	F	Weatherboard	2010-2019	Original	N3	HP	W	HP	W	150	100	1	1	1	1	0	Electric	Ripple	Elec	Idealistic
27	F	Brick	2010-2019	Upgraded	N3	HP+E	HP+E	HP+W	HP+W	150	100	1	1	1	1	0	Electric	Ripple	Elec	Idealistic
28	G	Sheet cladding	<1969	Original	N1	W	G	HP+E	HP+E	150	100	1	1	1	1	0	Electric	Ripple	Elec	Underheated
29	G	Weatherboard	2000-2009	Upgraded	N3	HP+E	HP+W	W+E	HP+W	150	100	1	1	1	1	0	Electric	Ripple	Elec	Realistic

HOUSEHOLD	TYPICAL BUILDING MODEL	WALL TYPE	DECADE BUILT (MIXED)	UPGRADED	INSULATION	HEATING EQUIP (AUK)	HEATING EQUIP (PN)	HEATING EQUIP (CAN)	HEATING EQUIP (DUN)	HWC VOLUME (L)	DHW DEMAND (L/DAY)	VEHICLE OWNERSHIP (AUK)	VEHICLE OWNERSHIP (CHC)	VEHICLE OWNERSHIP (PN)	VEHICLE OWNERSHIP (DUN)	EVs	HWC FUEL	RIPPLE	COOKING FUEL	HEATING BEHAVIOUR
30	G	Weatherboard	1990-1999	Original	N3	HP+E	HP+W	HP+W	HP+W	150	100	1	1	1	1	0	Electric	No ripple	Elec	Underheated
31	G	Concrete	1970-1979	Original	N1	HP+E	HP+E	HP+W	HP+W	150	100	1	1	1	1	0	Gas	No ripple	Gas	Realistic
32	G	Brick	1970-1979	Original	N1	G	HP+E	HP+E	HP+E	150	100	1	1	1	1	0	Electric	Ripple	Elec	Idealistic
33	H	Concrete	2020-2029	Original	N3	W	G	G	HP+E	150	100	1	1	1	1	0	Electric	No ripple	Elec	Idealistic
34	H	Sheet cladding	<1969	Upgraded	N2	HP	W	HP	W	150	150	2	2	2	2	0	Electric	No ripple	Elec	Underheated
35	H	Brick	2000-2009	Upgraded	N3	HP+E	HP+W	HP+W	HP+W	150	150	2	2	2	2	0	Electric	Ripple	Elec	Underheated
36	H	Sheet cladding	<1969	Upgraded	N2	HP	W	HP	G	150	150	2	2	2	2	0	Electric	No ripple	Elec	Idealistic
37	H	Brick	2020-2029	Original	N3	HP+E	HP+E	HP+W	HP+W	150	200	2	2	2	2	0	Electric	No ripple	Elec	Underheated
38	I	Concrete	<1969	Upgraded	N2	HP+E	HP+E	HP+W	HP+W	150	200	2	2	2	2	0	Electric	Ripple	Elec	Realistic
39	I	Sheet cladding	2010-2019	Original	N3	G	HP+E	HP+E	HP+E	150	200	2	2	2	2	0	Gas	No ripple	Elec	Realistic
40	I	Concrete	1990-1999	Original	N3	HP	G	HP	HP+E	150	200	2	2	2	2	0	Gas	No ripple	Elec	Idealistic
41	I	Sheet cladding	1980-1989	Upgraded	N2	W	G	HP	HP+E	150	200	2	2	2	2	0	Electric	No ripple	Gas	Idealistic
42	I	Brick	1980-1989	Original	N1	HP	W	HP	W	150	250	3	3	2	3	0	Electric	Ripple	Elec	Idealistic
43	J	Brick	1990-1999	Upgraded	N3	HP	W	HP	G	200	50	1	1	1	1	0	Electric	No ripple	Elec	Realistic
44	J	Weatherboard	1990-1999	Upgraded	N3	HP	W	HP	W	200	100	1	1	1	1	0	Electric	Ripple	Elec	Idealistic
45	J	Concrete	1970-1979	Upgraded	N2	HP	W	HP	W	200	100	1	1	1	1	0	Electric	Ripple	Elec	Underheated
46	J	Brick	<1969	Upgraded	N2	HP	W	HP	W	200	100	1	1	1	1	0	Electric	Ripple	Elec	Realistic
47	K	Brick	2010-2019	Original	N3	HP	W	HP	W	200	100	2	1	1	1	0	Electric	Ripple	Elec	Idealistic
48	K	Concrete	2000-2009	Original	N3	HP+E	HP+E	HP+E	HP+E	200	100	2	1	1	1	0	Electric	Ripple	Elec	Idealistic
49	K	Concrete	1970-1979	Upgraded	N2	HP+E	HP+E	HP+E	HP+E	200	100	2	2	1	1	0	Electric	Ripple	Elec	Realistic
50	L	Brick	2000-2009	Upgraded	N3	HP+E	HP+W	W+E	HP+W	200	150	2	2	2	2	0	Gas	No ripple	Elec	Idealistic
51	L	Brick	<1969	Upgraded	N2	HP	W	HP	W	200	150	2	2	2	2	0	Electric	No ripple	Elec	Realistic
52	L	Concrete	1970-1979	Original	N1	G	HP+E	HP+E	HP+E	200	150	2	2	2	2	0	Electric	Ripple	Elec	Realistic
53	M	Weatherboard	<1969	Original	N1	HP+E	HP+E	HP+W	HP+W	200	200	2	2	2	2	0	Electric	No ripple	Elec	Realistic
54	M	Brick	1990-1999	Original	N3	HP+E	HP+E	HP+E	HP+E	200	200	2	2	2	2	0	Electric	No ripple	Elec	Underheated
55	N	Weatherboard	<1969	Upgraded	N2	HP+E	HP+E	HP+E	HP+E	200	200	2	2	2	2	0	Electric	Ripple	Elec	Realistic
56	N	Brick	1990-1999	Original	N3	HP+E	HP+W	W+E	HP+W	200	250	3	3	3	3	0	Electric	Ripple	Elec	Underheated
57	O	Weatherboard	<1969	Upgraded	N2	W	G	G	HP+E	250	150	2	2	2	2	0	Gas	No ripple	Elec	Realistic
58	O	Brick	<1969	Upgraded	N2	HP+E	HP+W	HP+W	HP+W	250	200	2	2	2	2	0	Electric	Ripple	Elec	Underheated
59	O	Brick	2000-2009	Original	N3	HP	G	HP	G	250	250	3	3	3	3	0	Electric	Ripple	Gas	Underheated
60	O	Brick	1980-1989	Upgraded	N2	HP+E	HP+E	HP+W	HP+W	250	300	4	4	3	3	0	Electric	Ripple	Elec	Realistic

5.3 Building cluster formulation

5.3.1 *Physical building inputs*

Building inputs include the building floor area, number of floors, number of bedrooms, wall construction, and level of insulation for each household. The distribution of physical building characteristics (floor area, number of floors, number of bedrooms, wall construction) are derived from Christchurch City Council (CCC) building records. The dataset provided detailed building information not publicly available for the national or regional cases. The CCC building records closely match the national frequency of number of bedrooms for a household, taken from census data [8] and hence the CCC building records are assumed to be a suitable proxy for the national distribution. The number of different building models which compose the 60-household neighbourhood, along with their physical characteristics are shown in Table 5-7.

Table 5-7: Characteristics and quantity of buildings included in the analysis including the typical building model designation

BEDROOMS	FLOORS	FLOOR AREA	TB-MODEL	QUANTITY
1	1	<=115	A	4
2	1	<=115	B	4
2	1	115-151	C	4
2	2	<=115	D	4
3	1	115-151	E	6
3	1	151-188	F	5
3	1	188-234	G	5
3	1.5	151-188	H	5
3	2	115-151	I	5
4	1	151-188	J	4
4	1	188-234	K	3
4	1	>234	L	3
4	1.5	>234	M	2
4	2	>234	N	2
5+	1	>234	O	4
			Total	60

Four types of wall construction are included in the analysis, selected as the four most common types of construction in the CCC building records, which are: concrete block, brick, weatherboard, sheet-cladding. The proportion of the wall constructions utilised are shown in Figure 5-1.

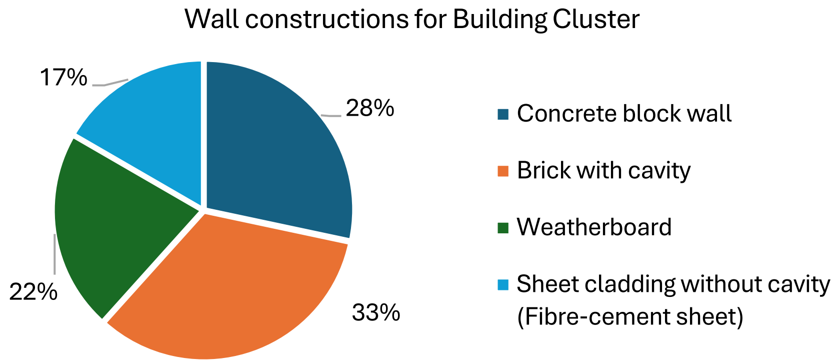

Figure 5-1: Proportion of wall-constructions used in the building cluster

The analysis included four levels of thermal efficiency, listed in Table 5-8. Where profile N4 is not used in the baseline case but is used in the insulation upgrade intervention.

Table 5-8: Building thermal efficiency profiles

PROFILE	DESCRIPTION	
N1	1977 insulation standard with wood-framed single glazing	[9]
N2	1977 insulation standard upgraded to Healthy Homes and with non-thermally broken aluminium frame double glazing	[9] [10]
N3	2007 insulation standard with thermally broken argon-filled aluminium frame double glazing	[11]
N4	CV5 + PVC frame triple glazing Argon filled	[12]

Insulation status is determined from building age with adjustments made for buildings with upgraded insulation. Building ages were determined and assigned from the distribution of building ages in the CCC building records for 'Mixed' clusters. Whereas all building in the 'old' clusters are aged '<1969' and 'new' clusters all '2010-2019'. A proportion of houses were determined to be rentals, determined by housing statistics: "Estimated number of private dwellings in New Zealand By tenure" [13], and were hence upgraded to the "Healthy Homes" insulations standards [10]. Further, a certain proportion of owner-occupied households were deemed to have been upgraded, using proportions published by the BRANZ Household Condition Survey (HCS) [14]. Hence, buildings were attributed an insulation status, "original" or "upgraded", and household insulation was determined from building age and whether the building was upgraded or not, as per Table 5-9.

Table 5-9: Categories of building age and insulation standard

	ORIGINAL	UPGRADED
<1969	N1	N2
1970-1979	N1	N2
1980-1989	N1	N2
1990-1999	N3	N3
2000-2009	N3	N3
2010-2019	N3	N3
2020-2029	N3	N3

5.3.2 *Occupancy and occupant behaviour*

Occupancy is assigned to households based on the number of bedrooms and overall household occupancy distributions, per census statistics [15], as shown in Table 5-10. Occupancy primarily drives DHW consumption, which is set to 50L per day per occupant [16].

Table 5-10: Household occupancy per number of bedrooms

BEDROOMS \ OCCUPANTS	1	2	3	4	5	6	7	8	*totals*
1	2	1	0	0	0	0	0	0	*3*
2	4	6	2	0	0	0	0	0	*12*
3	7	10	5	4	1	0	0	0	*27*
4	1	4	3	5	2	0	0	0	*15*
5	0	0	0	1	1	1	0	0	*3*
6	0	0	0	0	0	0	0	0	*0*
7	0	0	0	0	0	0	0	0	*0*
8	0	0	0	0	0	0	0	0	*0*
totals	*14*	*21*	*10*	*10*	*4*	*1*	*0*	*0*	60

Heating behaviour described the heating schedules and set points used for different living areas in buildings. Three types of heating behaviour are utilised following those used in EECA's Deep Retrofit Report and developed from the HEEP study, which are 'underheated', 'realistic', and 'idealistic'. These profiles are included in Appendix 5.5. Profiles are assigned in a distribution to approximate known space heating demands based on the HEEP study and EEUD [17], [18].

5.3.3 *Transport*

Vehicle ownership and travel demand vary based on region and whether the area is a Main Urban Area (MUA), Secondary Urban Area (SUA), or Rural location. In this work only Main Urban Areas are considered. The vehicle ownership and vehicle travel demands are assigned based on values derived from the Ministry of Transports Household Travel Survey (HTS). Vehicle ownership is and the distribution of vehicles in the BC are included in Table 5-11. Vehicle ownership is assigned to specific households based on occupancy, such that higher occupancy households have a greater number of vehicles. Travel demand based on fitted distributions from the HTS in included in Table 5-12.

Table 5-11: Proportion of households with certain numbers of vehicles and

		PROPORTION OF HOUSEHOLDS WITH N. VEHICLES (%)						
AREA TYPE	**REGION**	**0**	**1**	**2**	**3**	**4**	**5**	**6+**
MUA	Auckland	6.65	46.25	37	7.35	2.1	0.51	0.16
	Canterbury	7.42	49.67	33.92	6.58	2.08	0.33	0
	New Plymouth	10.68	52.57	30.6	5.13	1.03	0	0
	Otago	14.48	46.8	29.12	8.59	1.01	0	0

		NUMBER OF HOUSEHOLDS WITH N. VEHICLES IN BC						
AREA TYPE	**REGION**	**0**	**1**	**2**	**3**	**4**	**5**	**6+**
MUA	Auckland	4	28	23	4	1	0	0
	Canterbury	4	30	21	4	1	0	0
	New Plymouth	6	32	19	3	0	0	0
	Otago	8	29	18	5	0	0	0

Table 5-12: Fitted daily travel demand and percentage of days with no travel

AREA TYPE	DISTRIBUTION	REGION	SHAPE	LOC	SCALE	MEAN (km)	% DAYS NO TRAVEL (%)	90th PERCENTILE DAILY TRAVEL DISTANCE (km)	MAE (km)	MAPE (%)
MUA	Log normal	Auckland	1.059	0	23.29	40.8	36.50%	90.5	4.8	9.6
		Canterbury	1.018	0	19.755	33.2	37.00%	72.8	4.2	10.1
		New Plymouth	1.058	0	15.955	27.9	33.20%	61.9	7.1	12.9
		Otago	1.082	0	16.28	29.2	40.10%	65.2	4	8.0

EV uptake is set by annual fleet statistics [19]. In the baseline case, EV penetration is only 1.7% which corresponds to one vehicle in the 60-household cluster.

5.3.4 *Technological uptake*

Main technologies and fuels used for space heating by location was derived from the 2023 census responses to "Main types of heating used in New Zealand homes" [20]. The inverse method was applied to determine the combinations of technologies used, i.e. where a household heated with multiple fuels. The proportions of heating fuel per location are included in Table 5-13.

Table 5-13: Proportion of main heating sources for different locations

	PROPORTION				N. HOUSEHOLDS IN BC			
	AUCKLAND	NEW PLYMOUTH	CANTERBURY	OTAGO	AUCKLAND	NEW PLYMOUTH	CANTERBURY	OTAGO
HP	**29.6%**	2%	**32%**	1%	19	0	20	0
W	**13.3%**	**24%**	0%	**20%**	8	15	0	12
G	**12.5%**	**20%**	**8%**	**8%**	8	12	4	5
HP + E	**40.2%**	**34%**	**26%**	**39%**	25	21	16	23
HP + W	0.0%	**20%**	**24%**	**33%**	0	12	14	20
W + E	0.0%	0%	**10%**	0%	0	0	6	0
G + E	0.0%	0%	0%	0%	0	0	0	0
E	4.4%	0%	0%	0%	0	0	0	0

Where multiple fuels were used to heat a house, the proportion of heating energy consumed by each source was assumed to be that presented in Table 5-14 and heating source efficiency listed in Table 5-15.

Table 5-14: Proportion of heating by technology for the case where multiple heating technologies are used

	E	HP	W	G
HP+E	30%	70%	-	-
HP+W	-	50%	50%	-
W+E	-	30%	70%	-

Table 5-15: Efficiency of different heating technologies

HEATING TECHNOLOGY	EFFICIENCY
Wood stove	0.7
Gas heater	0.8
Electric resistive	1
Heat pump	4

Two fuel sources were considered for hot water heating, Gas and Electric. The proportion was 17% gas fuelled, and 83% electric fuelled, based on the household condition survey [14], which corresponds to 52 households with electric hot water heating and 8 households with gas hot water heating.

Electric Hot Water Cylinders (HWC) have characteristics derived from plumbing guidelines and the HEEP study [18]. A household has a HWC volume capacity based on the number of bedrooms (50L x number of bedrooms). Power capacities are set to 2.2kW, setpoints to 61°C. The proportion of households with ripple control is 52%, determined from the "Ripple control of Hot Water in New Zealand" report [21], which translates to 31 households in the cluster. The control signal for demand response is assumed to restrict heating during peak times (7am to 9:30am and 5:30pm to 8pm).

Households are considered to use either electricity or natural gas as a cooking fuel, which account for over 99% of cooking fuels, and the proportion of households using gas is determined to be 8.57%, which translates to 5 households using gas cooking.

Electric vehicles are represented by the 40 kWh Nissan Leaf [22], which is the most common type of electric vehicle [23]. The Nissan Leaf has a 39 kWh battery, and a mileage of 0.164 kWh/km. Battery charging efficiency is assumed to be 90%. The charger is the standard 2 kW trickle charger.

5.4 Urban energy model detailed modelling methodology

5.4.1 *Space heating load and typical buildings*

Space heating loads are imported from pre-simulated Building Energy Models (BEM) of Typical Buildings (TBs) that compose a Typical Building Library (TBL). Each household has an assigned TB. The TB BEM annual times series heating results are imported into the model. As the BEMs are simulated with uniform deterministic heating schedules, stochasticity must be added to avoid compounded aggregate loading. The imported heating loads are time-shifted (forward or backward) by a randomly number. The random number is generated from a distribution approximating the household departure times of the Ministry of Transport Household Travel Survey (HTS) [24].

Typical building library

The TBL contains 15 buildings and is designed to approximate the distribution of New Zealand Single Unit Dwellings (SUD), based on data attained from the Christchurch City Council (CCC). Building characteristics are listed in Table 5-16. The building models are high Level Of Detail

(LOD) models based on real buildings (hence "Typical") and modelled off building plans. Figure 5-2 includes images of a sample of TB models. The BEMs are fully zoned, i.e. they contain separate thermal zones for each of the conditioned areas (lounge, kitchen, bedroom), with fenestrations matching the real layout, shading to match window recession and eaves, and a thermal zone for the roof space. These features result in the most accurate building energy results, particularly time-based results [25].

Table 5-16: Characteristics of the 15 typical buildings included in the analysis

NUMBER OF BEDROOMS	FLOOR	AREA	BEDROOM	MODEL
1	1	<=115	1	A
2	1	<=115	2	B
2	1	115-151	2	C
2	2	<=115	2	D
3	1	115-151	3	E
3	1	151-188	3	F
3	1	188-234	3	G
3	1.5	151-188	3	H
3	2	115-151	3	I
4	1	151-188	4	J
4	1	188-234	4	K
4	1	>234	4	L
4	1.5	>234	4	M
4	2	>234	4	N
5	1	>234	5+	O

Figure 5-2: Images of sample typical building models demonstrating a range of floor levels

The building models are pre-simulated with multiple configurations: four wall types, four insulation levels, four heating behaviours, and four climate zones. In total 2880 configurations were simulated. These configurations are described below in Table 5-17. Other building simulation inputs are based on MBIE's "H1 Energy Efficiency Verification Method H1/VM1" [26] and professional judgement. Full inputs are available on request.

Table 5-17: Variables included in pre-simulation

VARIABLES	DESCRIPTION
Wall types	Brick
	Concrete
	Fibre-cement sheet clad
	Weatherboard clad
Insulation	NZS 4218: 1977
	NZS 4218: 1977 plus Healthy homes
	2007 Building Code H1 standard
	2023 Building Code H1 standard
Heating behaviours	"Idealistically heated"
	"Realistically heated"
	"Underheated"
Climates	Auckland
	Palmerston North
	Christchurch
	Dunedin

The wall-types included were based on the most commonly occurring, determined from querying the CCC buildings register. Insulation standards present a wide range of practically encountered and aspirational insulation levels. The heating behaviours are taken from the "Deep retrofit" report, which were derived from the BRANZ HEEP study [18]. The climates are the locations considered in this study and the climate files used were the NIWA derived Typical Meteorological Year (TMY) weather files derived from 2009-2023 [27].

For non-electric space-heating only the annual cumulative load is required. For households with a portion of non-electric heating, that share of the annual space heating demand is calculated and divided by the efficiency of the heating source to give energy demand for that source. Table 5-18 presents the heating technology efficiencies.

Table 5-18: Heating technology and assumed efficiency

HEATING TECHNOLOGY	EFFICIENCY
Wood stove	0.7
Gas heater	0.8
Electric resistive	1
Heat pump	4

5.4.2 *Plug loads and cooking loads*

Each household has a stochastic plug load and, if cooking is electrically fuelled, cooking load associated. Plug loads are here defined as any household load excluding hot water, electric vehicle charging, PV generation or battery charging and discharging, and oven or range loads. Cooking loads here only include the operation of an oven or range top. Upon initialisation of the UEM, each household imports a random plug and cooking profile from 300 profiles, where each profile includes one year of real, but modified, minute-by-minute plug or cooking loads data.

Plug loads and cooking loads are based on data extracted from the GreenGrid dataset [28]. Due to the limited number of households where adequate data was available, synthetic data was generated. Synthetic data was generated by creating pseudo years of data full of real days. The days were populated by sampling a day of real data from the donor data set. The data-day used was within +- 10 days of the day being populated, hence maintaining seasonal trends. Overall, the approach bridges the lack of data available and produces realistic time-based plug and cooking loads, maintain the daily and seasonal patterns of demand.

5.4.3 *Hot water heating*

Hot water heating calculations utilises a simple thermal model (fully fixed) of an electric Hot Water Cylinder (HWC), where the model implementation follows this work [6], [29]. The sub-model takes HWC the input parameters detailed in Table 5-19. An energy balance is conducted each minute to calculate the new cylinder temperature, considering Domestic Hot Water (DHW) draw and heating power. Hot water heat pumps are simply modelled assuming a constant COP and implemented by modifying the heating efficiency. Note the heating efficiency refers to the heating element and does not account for heat losses due conduction through walls, which is accounted for elsewhere.

Table 5-19: Inputs for the HWC sub-model with example values

DHW daily demand (L)	50 [30]
HWC heating efficiency	1
HWC heating capacity (kW)	2.2
HWC setpoint (°C)	61
HWC control schedule	"OffPeak (700-930_1730-2000)"
HWC control strategy	"Schedule-Setpoint"

DHW profiles are annual minute by minute stochastic profiles that characterise the temporal hot water draws, pre-generated using DHWCalc [31]. The first level of heating control is thermostat based, where the heating element switches on below the setpoint and off above the setpoint. Secondly, time-based schedules can be imposed that restrict when the cylinder can turn on or off. Figure 5-3 demonstrates simulated hot water cylinder performance and the DHW and control signal inputs.

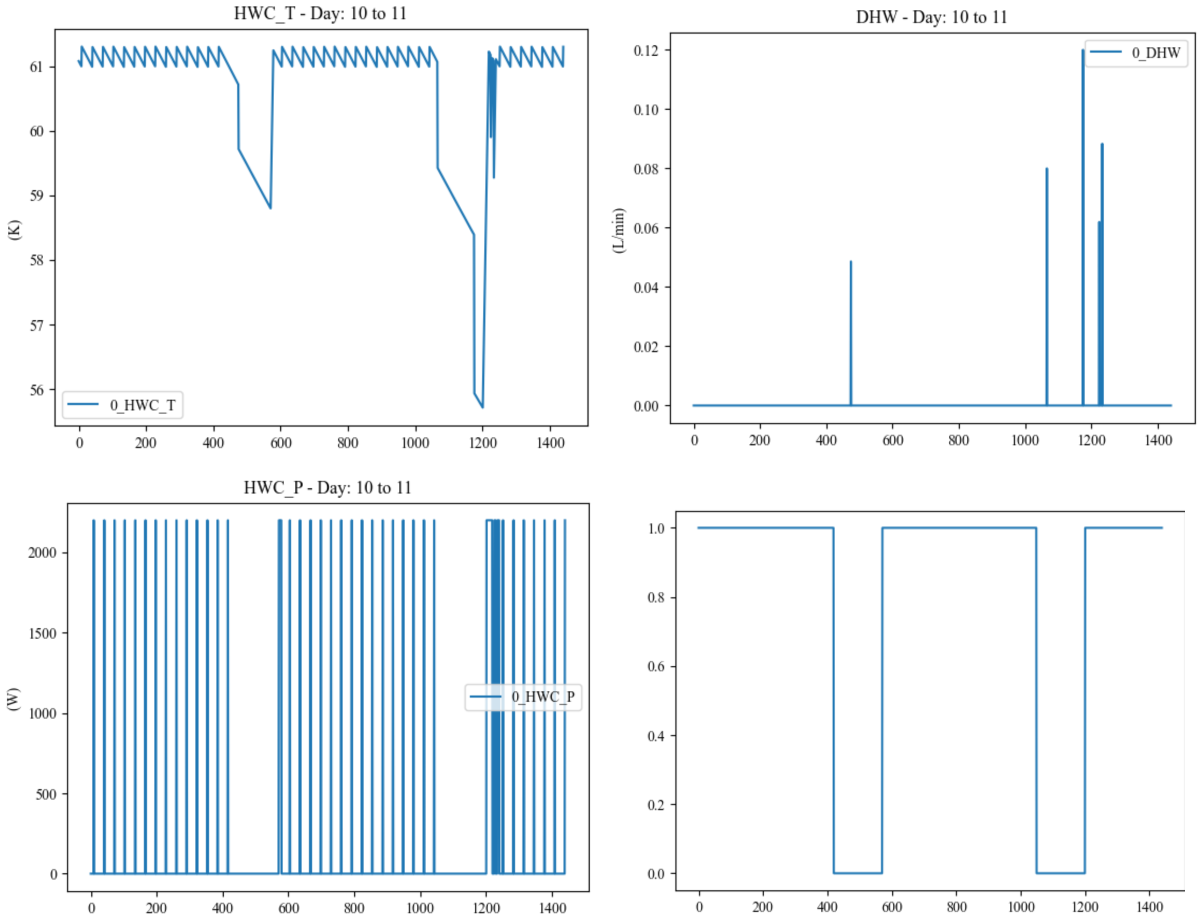

Figure 5-3: Simulated HWC performance for a sample day, where the x-axis denotes minutes in the day, figures include temperature (top left), DHW consumption (top right).power demand (bottom left), Time-based control window (bottom right), where 1 indicates the cylinder can turn on and 0 the cylinder is restricted from turning on

Where gas is used to heat hot water, only the annual figure is required. The energy required is heat the annual DHW consumption from 16°C to 50°C, accounting for 20% losses.

5.4.4 *Electric vehicle charging*

The electric vehicle sub-model includes a physics-based model of car battery charging and discharging, due to imposed travel demands. The model is agent-based and follows a similar logic to [32]. Inputs for the battery model are included in Table 5-20 and model inputs for vehicle travel demand are included in Table 5-21. An energy balance is conducted on the car battery each timestep, however travel demand is imposed (if any) as a concentrated load at midday.

Table 5-20: Inputs for the EV sub-model with example values

Battery capacity (kWh)	39
Charging efficiency	0.9
Charging capacity	7
Mileage (kWh/km)	0.164
EV control schedule	"130am-530amAND1130am-330pm"

Table 5-21: Travel demand inputs for the EV sub-model with example values

Distribution	"lognorm"
Distribution shape parameter	1.059
Distribution scale parameter	23.29
Percentage non travel	0.365

Annual daily travel demands for each vehicle are generated at model initialisation. For each day it is decided if the vehicle travels using the "percent no travel" input, and if the vehicle does travel, a daily travel distance is generated according to the statistical distribution and associated input parameters. Additionally, if the vehicle departs home that day, vehicle departure and return times are generated by sampling real times from the HTS.

For each minute the battery model checks if the vehicle is at home and, if a control schedule is implemented, whether charging is allowed, if these are both true the vehicle charges. The vehicle charges to the maximum of either the charging capacity less the charging losses or the battery charging function less the charging losses. The battery charging function relates charging rate with battery State Of Charge (SOC), reflecting reduced charging power and higher SOC. The charging curve follows a standard equation, as used in this work [32]. Travel demands are imposed on the vehicle as a concentrated load at midday. Example results of EV simulation are included in Figure 5-4.

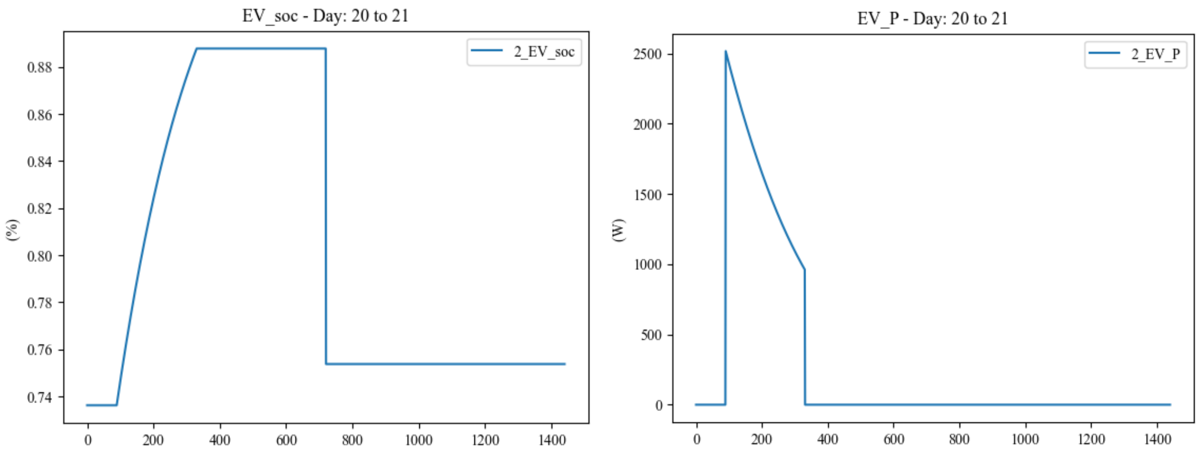

Figure 5-4: Simulated EV performance for a sample day, where the x-axis denotes minutes in the day. Figures include EV battery SOC (left) and charging power (right)

Cumulative non-electric transportation demand, kilometres travelled, is calculated by multiplying the mean daily travel demand by the number of days in a year and the percentage of days with no travel. The number of kilometres travelled by diesel and petrol vehicles are calculated by the fractions in

Table 5-22, where the figures are derived from the MoT annual fleet statistics for light passenger vehicles [19]. Energy for transportation is calculated by multiplying kilometres travelled for each source by the energy required per kilometre, these figures are derived using the EECA Energy End Use Database and MoT annual fleet statistics [19].

Table 5-22: Kilometres travelled by vehicle fuel source and energy used per km by fuel

FUEL FRACTIONS PER KM	
Diesel fraction of km	0.13
Petrol fraction of km	0.87

ENERGY PER KM	
Petrol (kWh/km)	0.75
Diesel (kWh/km)	0.96

5.4.5 *Roof top solar photovoltaic generation*

Physical models of PV generation are utilised. For each array, PV generation is calculated from weather files using a transposition model. The PV sub model takes a range of physical inputs for each array, summarised in Table 5-23. The weather files used are the 2009-2023 TMY files which match the weather files used to simulate building heating loads.

Table 5-23: Inputs for the solar-PV sub-model with example values

Power of array (Wp)	5000
Temperature coefficient (%/°C)	-0.004
Surface tilt (°)	28
Surface azimuth (°)	6

Solar generation is calculated for the year at model initialisation for each array. The effect of local and topographical shading is ignored. Example results for Solar PV generation are included in Figure 5-5, where generation is denoted as a negative load.

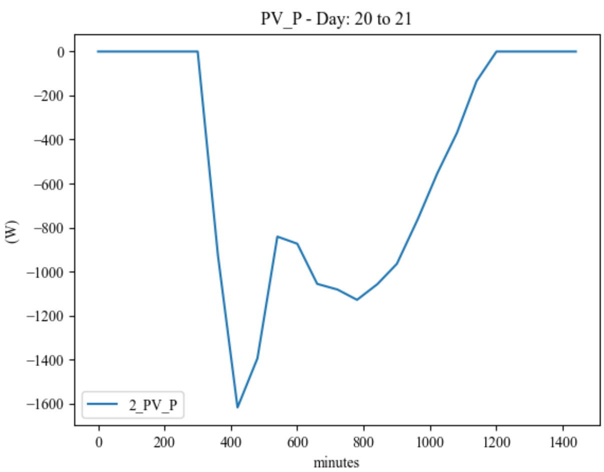

Figure 5-5: Simulated PV generation for a sample day.

5.4.6 *Domestic batteries*

Physical models of domestic batteries are included. The sub-model simulates the charging and discharging of batteries, performing an energy balance every timestep. When charging, the battery charges the maximum of either the charging capacity less the charging losses or the battery charging function less the charging losses, like the methodology for Electric Vehicle batteries. The charging curve follows a standard equation. Battery discharging is limited by the discharge rate or required discharge regulated by the control logic.

Table 5-24: Inputs for the battery sub-model with example values

Battery power capacity in (kW)	3.3
Battery power capacity out (kW)	3.3
Battery efficiency charge	0.9
Battery efficiency discharge	0.9
Battery control schedule	"130am-530amAND1130am-330pm"
Battery control strategy	"off-peak schedule charge HH_peak_reduction"

Domestic battery control is more involved than other sub-models. Charging and discharging can be schedule-based, rule-based, or both. Schedules restrict times for charging and discharging, whereas rules-based controls relate charging or discharging magnitude to variables. For example, schedule-based control is utilised to charge batteries during off-peak times, however rules-based control is required to discharge batteries in proportion to household peaks for peak-load mitigation.

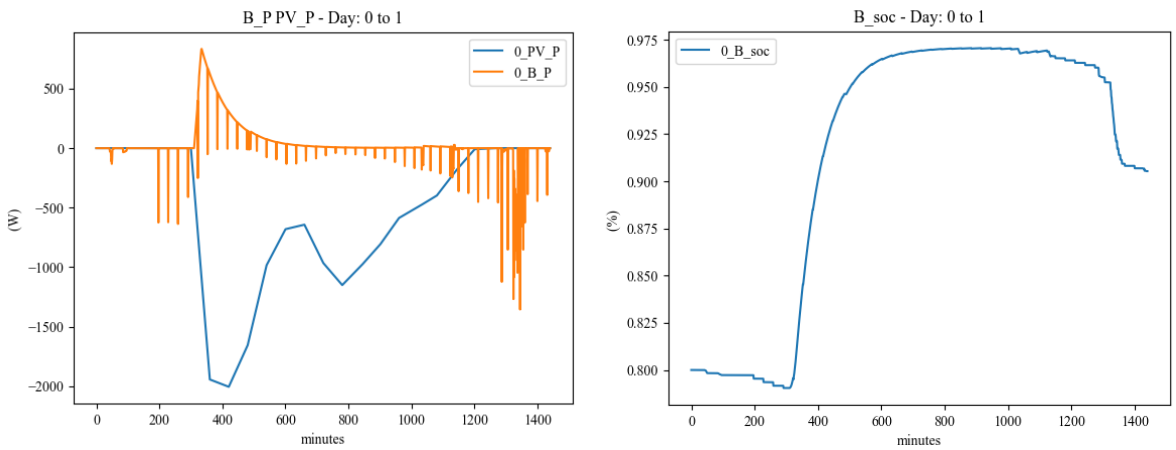

Figure 5-6: Simulated battery charging and discharging for a sample day (left) demonstrates battery charging with PV generation and discharging to meet peak loads (right) battery state of charge

5.4.7 *Emissions intensity figures*

Emissions intensity calculations depend on several specific energies, energy densities, and carbon emissions factors. These figures are included in Table 5-25.

Table 5-25: Carbon intensity per fuel source

Gas	0.194	kg CO_2e/kWh
Wood	0.0176667	kg CO_2e/kWh
Electricity – grid	0.10278	kg CO_2e/kWh
Petrol	0.248	kg CO_2e/kWh
Diesel	0.254	kg CO_2e/kWh

5.5 Typical building model inputs

Table 5-26: Heating behavioural profiles

	HEATING SCHEDULE					
	HEATING SETPOINT (ºC) – WEEK			HEATING SETPOINT (ºC) – WEEKEND		
HOURS OF DAY	LIVING ROOMS (dining, kitchen, living)	BEDROOMS	WCS/CORRIDORS	LIVING ROOMS (dining, kitchen, living)	BEDROOMS	WCS/CORRIDORS
UNDERHEATED						
12 am - 7 am	N/A	N/A	N/A	N/A	N/A	N/A
7 am - 9 am	16	14	N/A	16	14	N/A
9 am - 5 pm	N/A	N/A	N/A	16	N/A	N/A
5 pm - 7 pm	16	N/A	N/A	16	N/A	N/A
7 pm - 11 pm	16	14	N/A	16	14	N/A
11 pm - 12 am	N/A	N/A	N/A	N/A	N/A	N/A
IDEALISTIC						
12 am - 7 am	N/A	N/A	N/A	N/A	N/A	N/A
7 am - 9 am	20	18	N/A	20	18	N/A
9 am - 5 pm	N/A	N/A	N/A	20	N/A	N/A
5 pm - 7 pm	20	N/A	N/A	20	N/A	N/A
7 pm - 11 pm	20	18	N/A	20	18	N/A
11 pm - 12 am	N/A	N/A	N/A	N/A	N/A	N/A
REALISTIC						
12 am - 7 am	N/A	16	N/A	N/A	16	N/A
7 am - 9 am	20	18	N/A	20	18	N/A
9 am - 5 pm	N/A	N/A	N/A	20	N/A	N/A
5 pm - 7 pm	20	N/A	N/A	20	N/A	N/A
7 pm - 11 pm	20	18	N/A	20	18	N/A
11 pm - 12 am	N/A	16	N/A	N/A	16	N/A

5.6 Urban energy model verification

To verify the modelling approach the results of simulated baseline models are compared against reference values. Household electricity consumption is compared against the national average, household operating GHG emissions due to transport and non-transport are compared against national figures, household contribution to cluster peak demand (i.e maximum demand divided by the number of households) is compared against After Diversity Maximum Demand (ADMD) figures for two Christchurch Medium Voltage (MV) networks with approximately 2000 households. Finally, district end-use breakdown is compared to the results attained by the Household Energy End-use Project. The simulation values and relevant reference values are compared in Table 5-27, and energy end-use breakdown is compared in Table 5-12.

Table 5-27: Comparison of per household simulated and reference values, where needed normalised to household values from StatsNZ datasets [33]

AVERAGE VALUES PER HOUSEHOLD	SIMULATION	REFERENCE	DIFFERENCE	REFERENCE
Electricity total (MWh)	5.95	7.15	-17%	[34]
Carbon non-transport (T)	0.74	0.48	53%	[35]
Carbon transport (T)	2.10	3.91	-46%	[35]
Carbon total (T)	2.83	4.39	-36%	[35]
After diversity max demand (kW)	2.98	2.6 - 3	0%	[36]

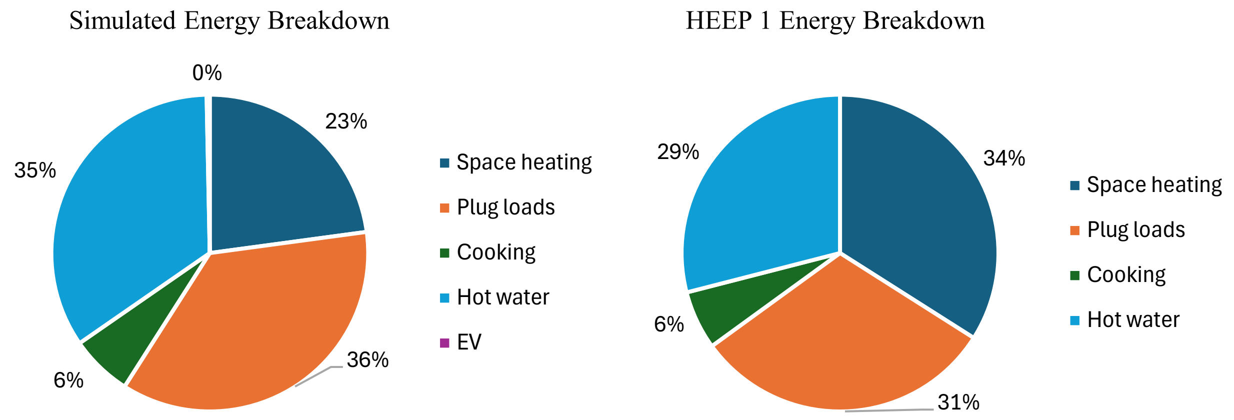

Figure 5-7: Breakdown of simulation energy end-uses versus HEEP 1 end use breakdown [18]

Generally, the average simulation results compare well with the reference values, indicating the results attained from this research are reasonably accurate. So, relative impacts from DEEDs interventions and pathways, attained from this research, can be treated as being reasonably accurate.

There are two significant reasons to expect a mismatch between national reference values and the baseline simulation results: (1) the composition of households and occupants in the BC's does not fully match the national case, and (2) the four locations monitored are not fully representative of the whole of New Zealand. So, a perfect match is not expected, however the results discrepancies are within reasonable bounds, which indicates the UEM developed here does a reasonably good job of assessing the relative impacts of various energy interventions and pathways.

Simulated electricity consumption is 17% below the reference value. There is a greater deviation in operating GHG emissions, where non transport emissions for the simulated BCs exceed the national average by 53%, and transport emissions are 46% less than the national average. The difference in transport emissions is due to MUAs being used in the analysis, which have lower travel demand and vehicle ownership than SUA and Rural areas. Whereas the reference values for non-transport household emissions (0.48T CO_2e/household) seems too low as taking average annual household electricity consumption (7150 kWh/household) and the average grid emissions factor (0.102 kgCO_2e/kWh) easily exceeds the reference value (0.715T CO_2e/household) and more closely aligns with the simulated value (0.740T CO_2e/household). So, overall, the differences in operating GHG emissions can be explained and align well with simulated values.

A key concern of this research is the impact of the 'DEEDs' on peak power demands. The maximum demand normalised to household for the simulated values is (2.98 kW/household) which agrees well with the reference values provided by EDB Orion (2.6-3 kW/household). It should be noted; the simulated results are less diversified (60 households) than the ADMD reference values (~2000 households). Further diversification will generally reduce ADMD and hence the simulated results look more favourable moving closer to the middle of the reference range.

Finally, the simulated breakdown of energy end-use compares well with reference values. The largest discrepancy is in space heating (simulated equals 23% versus reference equals 34%). However, the HEEP study was conducted over several years between 1997-2005 and hence does not reflect changes since that time. One major change since the HEEP data was collected is the greater use of electric heat pumps for space heating, which can significantly reduce space heating energy consumption (although the takeback effect leads occupants to heat their houses more which offsets some energy savings). The adoption of heat pumps can easily account for the 11% difference between simulated results and HEEP data. Taking the uptake of heat pumps into account, the simulated energy end use proportions are in good agreement with reference values.

6. References

[1] Ministry for the Environment, “New Zealands second emissions reduction plan 2026-30,” 2023.

[2] Heathcotes, “Heathcotes - Fujitsu Heat Pump,” Heathcotes. Accessed: Jun. 12, 2025. [Online]. Available: https://www.heathcotes.co.nz/products/asth18kmtd-fujitsu-5-0-kw-cooling-and-6-0-kw-heating-wall-mounted-kmtc-heat-pump-air-conditioner?taxon_id=78

[3] Standards New Zealand, “ASNZS-3823-4-22014A1 Performance of electrical appliances - Air conditioners and heat pumps,” 2014.

[4] Rheem, “Rheem Ambiheat Heat Pump,” Rheem. Accessed: Jun. 12, 2025. [Online]. Available: https://rheem.co.nz/products/home/heat-pump-water-heating/ambiheat-heat-pump/a55127005

[5] Standards New Zealand, “ASNZS-5125-12014 Heat pump water heaters performance assessment,” 2014.

[6] D. Bishop, T. Nankivell, and B. Williams, “Peak loads vs. cold showers: the impact of existing and emerging hot water controllers on load management,” *J R Soc N Z*, 2023, doi: 10.1080/03036758.2023.2286988.

[7] I. Khan, M. W. Jack, and J. Stephenson, “Analysis of greenhouse gas emissions in electricity systems using time-varying carbon intensity,” *J Clean Prod*, vol. 184, pp. 1091–1101, May 2018, doi: 10.1016/j.jclepro.2018.02.309.

[8] Stats NZ, “Census: Totals by topic for dwellings, (NZ total), 2013, 2018, and 2023 Censuses,” StatsNZ. Accessed: Jan. 06, 2025. [Online]. Available: https://figure.nz/chart/uFbVQ8Nacmt3w55y

[9] Standards New Zealand, “AS/NZS 3823.4.2:2014 - Performance of electrical appliances- Air conditioners and heat pumps,” 2014. Accessed: Jan. 06, 2025. [Online]. Available: https://www.standards.govt.nz/shop/nzs-4218p1977

[10] TenancyServices, “Healthy homes,” TenancyServices. Accessed: Jan. 06, 2025. [Online]. Available: https://www.tenancy.govt.nz/healthy-homes/

[11] Ministry of Business Innovation and Employment, “H1 Energy Efficiency Acceptable solution H1/AS1 2007,” Department of Building and Housing, 2014.

[12] Ministry of Business Innovation and Employment, “H1 Energy Efficiency Acceptable Solution H1/AS1 2022.” [Online]. Available: www.building.govt.nz

[13] Stats NZ, “Estimates and Projections: Estimated Private Dwellings, As At Quarter Ended June 2024,” Stats NZ. Accessed: Jan. 06, 2025. [Online]. Available: https://figure.nz/chart/bOXOzYWW8RyIotwx

[14] V. White, M. Jones, V. Cowan, and S. Chun, “Study report SR370 BRANZ 2015 House Condition Survey: Comparison of house condition by tenure,” 2015.

[15] Stats NZ, “Census - Number of usual residents in household by number of rooms and territorial authority 2018,” 2018. Accessed: Jan. 06, 2025. [Online]. Available: https://figure.nz/table/M2PuTABwiErXOdoH

[16] Sustainable Energy Transformation Pty Ltd, “understanding which factors influence a proposed household hot water draw-off profile study,” Jun. 2019.

[17] Energy Efficiency & Conservation Authority, “Energy End Use Database,” Energy End Use Database. Accessed: Jan. 06, 2025. [Online]. Available: https://www.eeca.govt.nz/insights/data-tools/energy-end-use-database/

[18] N. Isaacs *et al.*, "Study report SR221 Energy use in New Zealand households: Final report on the household energy end-use project (HEEP)," *STUDY REPORT SR*, vol. 221, 2010.

[19] Ministry of Transport, "Annual fleet statistics," Annual fleet statistics. Accessed: Jan. 06, 2025. [Online]. Available: https://www.transport.govt.nz/statistics-and-insights/fleet-statistics/sheet/annual-fleet-statistics

[20] Stats NZ, "Main types of heating used in New Zealand homes 2013, 2018, & 2023 Census," Stats NZ. Accessed: Jan. 06, 2025. [Online]. Available: https://figure.nz/chart/YhQCiWmti47I0sr2

[21] Energy Efficiency Conservation Authority, "Ripple Control of Hot Water in New Zealand," 2020. [Online]. Available: www.eeca.govt.nz

[22] EVDB, "Nissan Leaf," EVDB. Accessed: Jan. 06, 2025. [Online]. Available: https://evdb.nz/v/nissan-leaf

[23] EVDB, "Most Popular EVs in New Zealand," EVDB. Accessed: Jan. 06, 2025. [Online]. Available: https://evdb.nz/most-popular-evs-nz

[24] Ministry of Transport, "New Zealand Household Travel Survey," New Zealand Household Travel Survey. Accessed: Jan. 06, 2025. [Online]. Available: https://www.transport.govt.nz/area-of-interest/public-transport/new-zealand-household-travel-survey

[25] D. Bishop, M. Mohkam, B. L. M. Williams, W. Wu, and L. Bellamy, "The Impact of Building Level of Detail Modelling Strategies: Insights into Building and Urban Energy Modelling," *Eng*, vol. 5, no. 3, pp. 2280–2299, Sep. 2024, doi: 10.3390/eng5030118.

[26] Ministry of Business Innovation and Employment, "H1 Energy Efficiency Verification Method H1/VM1 2022." [Online]. Available: www.building.govt.nz.

[27] NIWA, "Typical Meteorological Year 2009-2023," NIWA. Accessed: Jan. 06, 2025. [Online]. Available: https://data.niwa.co.nz/

[28] J. Stephenson, R. Ford, N. K. Nair, N. Watson, A. Wood, and A. Miller, "Smart grid research in New Zealand – A review from the GREEN Grid research programme," Feb. 01, 2018, *Elsevier Ltd.* doi: 10.1016/j.rser.2017.07.010.

[29] B. Williams, D. Bishop, and P. Docherty, "Assessing the energy storage potential of electric hot water cylinders with stochastic model-based control," *J R Soc N Z*, pp. 1–17, Apr. 2023, doi: 10.1080/03036758.2023.2197241.

[30] Sustainable Energy Transformation Pty Ltd, "UNDERSTANDING WHICH FACTORS INFLUENCE A PROPOSED HOUSEHOLD HOT WATER DRAW-OFF PROFILE STUDY," 2019.

[31] U. Jordan and K. Vajen, "DHWcalc: PROGRAM TO GENERATE DOMESTIC HOT WATER PROFILES WITH STATISTICAL MEANS FOR USER DEFINED CONDITIONS," 2005. [Online]. Available: www.solar.uni-kassel.de.

[32] B. Williams, D. Bishop, G. Hooper, and J. G. Chase, "Driving change: Electric vehicle charging behavior and peak loading," *Renewable and Sustainable Energy Reviews*, vol. 189, Jan. 2024, doi: 10.1016/j.rser.2023.113953.

[33] Stats NZ, "Number of estimated and projected households by type," Stats NZ. Accessed: Jan. 06, 2025. [Online]. Available: https://www.stats.govt.nz/topics/households

[34] Ministry of Business Innovation and Employment, "Electricity cost and price monitoring," Electricity cost and price monitoring. Accessed: Jan. 06, 2025. [Online]. Available: 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

[35] Stats NZ, "Greenhouse gas emissions (industry and household): March 2024 quarter," Stats NZ. Accessed: Jan. 06, 2025. [Online]. Available: https://www.stats.govt.nz/information-releases/greenhouse-gas-emissions-industry-and-household-march-2024-quarter/#:~:text=Seasonally%20adjusted%20total%20emissions%20were,1.4%20per cent%20(154%20kt).

[36] Orion, "Orion Asset Management Plan 2018," 2018.