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Contributions

Carsten Dortans conducted the bulk of the literature review, data sourcing, data processing, data analysis and writing of the report.

Ben Anderson provided preliminary data analysis of overall demand, gave advice on data analysis and results presentation and contributed to the final report.

Michael Jack co-secured the funding to support the work, gave advice on data sources, data analysis, results presentation, commercial and policy implications and contributed to the final report.

Janet Stephenson co-secured the funding to support the work, gave advice on results presentation and policy implications and contributed to the final report.

Citation and usage license

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List of Abbreviations

CPD	Congestion period demand
DR	Electricity demand response
EECA	Energy Efficiency and Conservation Authority
GWh	Gigawatt hour
MWh	Megawatt hour
TOU	Time-of-use

Executive summary

This report estimates the maximum technical potential for demand response (DR) for three appliances in New Zealand's residential sector. On-demand electricity load reduction, particularly at times of peak demand, enhances the system operationality and reduces stress on the utility grid. This is increasingly important as the supply of variable renewables, such as solar and wind, increases. As load reduction during peaks can reduce underutilized generation and transmission capacity it has a significant economic benefit and can also lower the cost of integrating renewables into the grid.

To estimate the technical potential for demand response in the residential sector, we integrated a variety of data sources to construct average electricity demand profiles of three key residential appliances: heat pumps, hot water heaters and refrigerators. We then used simple DR scenarios, including load shifting to off-peak intervals, to determine the national potential for load reduction. The economic values of these scenarios were then estimated using current time-varying electricity prices and typical congestion period charges.

The study focused on load reduction and load shifting of household appliances that possess storage ability such as heat pumps, hot water heaters, and refrigerators. To estimate the technical potential, any current use of hot water heaters for DR is neglected. These appliances can operate at times prior to peaks without significant impact on service (e.g. hot water can be stored in the hot water cylinder).

Fig. 1 portrays the effects of the DR scenarios on total electricity demand in New Zealand. These show that DR can reduce load during the winter morning peak period by 20% and by 18% in the evening. This equates to an average daily energy reduction of 5,100 MWh in the morning peak and 4,900 MWh in the evening peak. In the summer, less utilisation of heat pumps in the morning peak decreases this proportion to 15% and 14% in the evening. In combination, the appliances modelled could provide a maximum aggregated demand response of 1,600 MW in the winter morning peak, and 1,200 MW in the evening peak. This technical potential amounts to 2.5 times Transpower's proposed DR programme of 635 MW from both industrial and residential DR (Transpower New Zealand Limited, 2014).

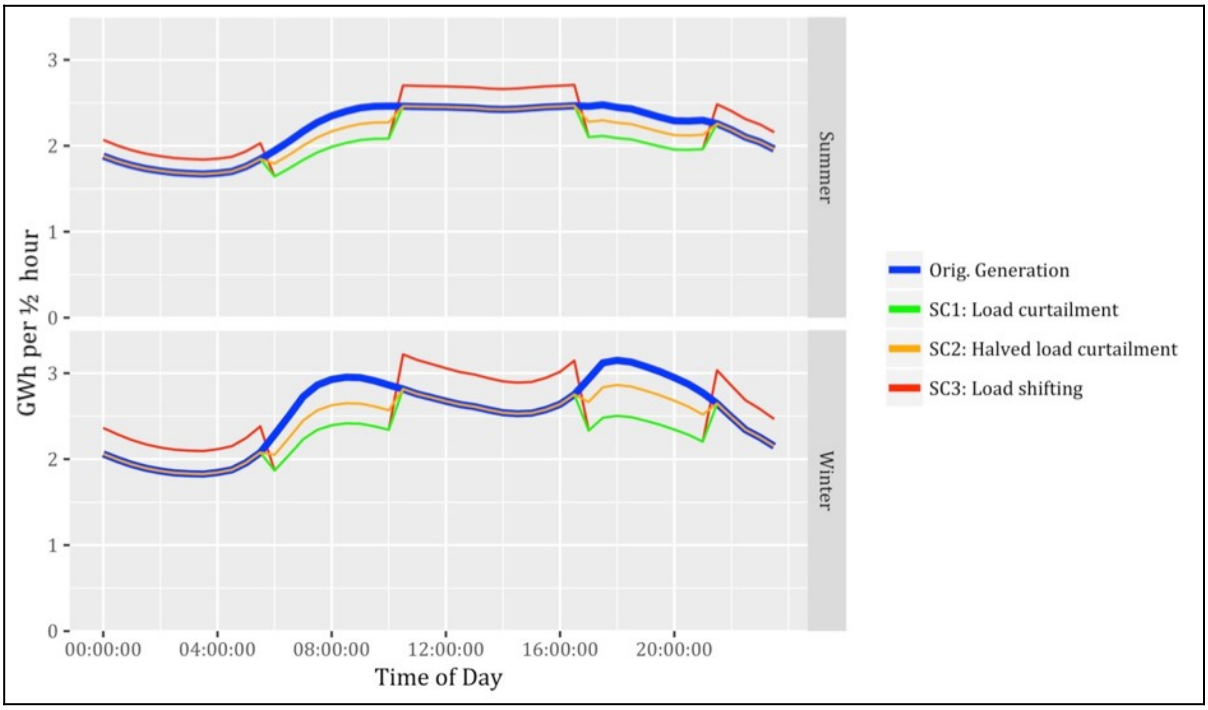


Fig. 1| Estimated daily effects of DR scenarios 1-3 on total electricity generation

Furthermore, Figure 1 shows a new steep-edged peak caused by the simple abrupt load shifting scenario which results in increased electricity demand in the middle of the day in both summer and winter. This could be considered as part of a future high install level scenario for photovoltaic generation. It should be noted that the red line of scenario three at reduced peaks is overlaid by scenario one. Both scenarios display the same energy reduction during times of peaks.

Based on current time-varying prices and typical congestion charges, the economic value of shifting this load out of peak intervals was estimated to be up to $72 million NZD per year.

It should be noted that this report focused on the *technical* potential of residential DR and aims to estimate the maximum energy potential (and its economic value) that may be available to shift. The market mechanisms, technology, and behavioural change required to realise this potential was not considered in the analysis and remains an open challenge as does the availability of more up-to-date data which can increase the accuracy of future iterations of this work.

1 Introduction

There are significant national drivers for renewable energy sources (RES) to ensure low-carbon supply into New Zealand's electricity system. However, RES are often highly dependent on environmental conditions due to the volatile nature of solar irradiance, wind speed, and inflow of water into hydro lakes. This affects the amount of electricity that can be generated (Müller & Möst, 2018). These changing environmental conditions cause fluctuations in electricity generation and require measures to ensure the balance between electricity supply and electricity consumption (O'Connell, Pinson, Madsen, & O'-Malley, 2014).

As an important example, electricity supply systems must be able to meet peak electricity demand. Since peak demand does not require all of the electricity system's generation and transmission infrastructure at all times, peaks significantly larger than the average result in an under-utilisation of installed network components (Albadi & El-Saadany, 2007). In addition, electricity peak demand has the potential of causing stress on the utility grid. These issues are likely to be exacerbated with more variable RES. To ensure an economically-efficient, low-carbon electricity system, particularly during times of peak demand with a restricted availability of RES electricity generation, mechanisms focusing on the management of electricity demand are necessary. Demand response (DR) is one mechanism to counter these challenges in electricity supply and demand.

One definition of DR is:

> *"[…] end-use consumers intentionally altering their normal consumption patterns (by changing their instantaneous demand for electricity, the timing of their electricity consumption, or their total consumption of electricity), in response to electricity price changes, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardised."* (Electricity Authority, 2015, pp. 1-2).

This definition incorporates DR definitions from the U. S. Department of Energy, the Federal Energy Regulatory Commission (FERC), and the pan-European Union of the Electricity Industry (Eurelectric). Electricity Efficiency is excluded from this definition as it reduces electricity demand in general and does not take variable conditions in electricity generation into account (Electricity Authority, 2015). Based on the definition above, DR comprises mechanisms that change the consumption pattern of electricity consumers and can assist to retain and improve the electricity system's low-carbon properties, and security of electricity supply.

DR can be seen as a measure that relieves stress on the utility grid. During times of peak electricity use, DR enables actions at the customer's appliance or equipment that are capable of shifting or shedding power demand. One approach to implement DR is to try and affect customer's electricity consumption behaviour using price signals. This encourages participants to utilise electricity during times of a relatively lower overall electricity demand. This DR might be implemented by automated processes, or aggregators since the transaction cost for having the residential customer watching the electricity price is likely to be higher than the actual cost per hour on electricity.

While a number of mature DR mechanisms exist in the industrial and commercial sector, the potential for DR in the residential sector is less well explored (see section 3.3) even though the residential sector is the main contributor to peak demand in New Zealand. This paper estimates the technical potential of residential DR focusing on residential hot water heaters, heat pumps, and refrigeration. These appliances constitute a significant component of electricity consumption of residential households in New Zealand (Burrough, 2010) and also make up a significant component of consumption during peak time periods. In addition, these thermo-electric appliances have the ability to store energy in the form of heat or cold, providing a time buffer between electricity demand and the service they provide. In this report, we focus on the ***technical potential*** of DR in New Zealand by estimating the total power that could in principle be reduced or shifted based on the aforementioned analysed load profiles of residential household appliances. We develop DR scenarios consisting of full load curtailment (scenario **one**), halved load curtailment (scenario **two**), and load shifting (scenario **three**). Please note that scenarios one and two are simply used to quantify the demand that can be shifted at peak times and are unlikely to be implemented. We also estimate the economic value of these scenarios based on current time-varying prices and typical congestion charges. We leave analysis of the technological, market and social innovations required to implement these scenarios to future work.

This work aims to:

- **Estimate the technical potential of residential DR by**

    1. Utilising electricity load profiles including appliances with significant electricity consumption in households (hot water heaters, heat pumps, and refrigeration)

    2. Developing DR scenarios that include load curtailment and load shifting during peak times

    3. Estimating the load reduction potential of residential DR based on electricity load profiles and DR scenarios

    4. Estimating the economic value of the residential DR scenarios based on current DR mechanisms (spot market prices and CPD charges)

The structure of this report is as follows:

Section 1 introduces residential electricity DR mechanisms. Section 2 depicts electricity supply and demand in New Zealand and identifies household appliances suitable for DR. Section 3 elucidates DR mechanisms and presents examples of how these mechanisms are implemented in the current New Zealand electricity system. Section 4 explains the data sources and methodologies utilised in the analysis. Section 5 presents the results of estimating the technical potential of residential DR in New Zealand and distinguishes between energy and economic DR potential. Section 5 ignores practicality issues generated by DR scenarios but focuses on the maximum technical potential of DR. Costs in the following are always cited in $NZ and figures depict local New Zealand time for the relevant month. Section 6 summarises the key findings of this report and suggests areas of further work as well as limitations of the analysis.

2 Electricity supply and demand in New Zealand

Unlike electricity networks in Europe, New Zealand's geographic location necessitates energy management without the opportunity of interacting with adjacent countries. New Zealand, therefore, relies on national electricity generation and especially national demand management. Electricity supply and electricity demand are strongly inter-connected. The requirement to maintain a balance between electricity supply and demand means an analysis of DR potential also requires consideration of electricity supply. In this section, a brief summary of current electricity supply and demand in New Zealand is presented.

2.1 Electricity supply

Fig. 2 shows the total electricity generation in NZ for each fuel in June and December 2017. There is a higher electricity generation in June (3,600 GWh) compared to December (3,300 GWh). More than half of the total electricity was supplied by hydro electricity generation and geothermal and gas each supplied 700 GWh per month. Wind and coal electricity generation take on a minor proportion of 100 GWh per month.

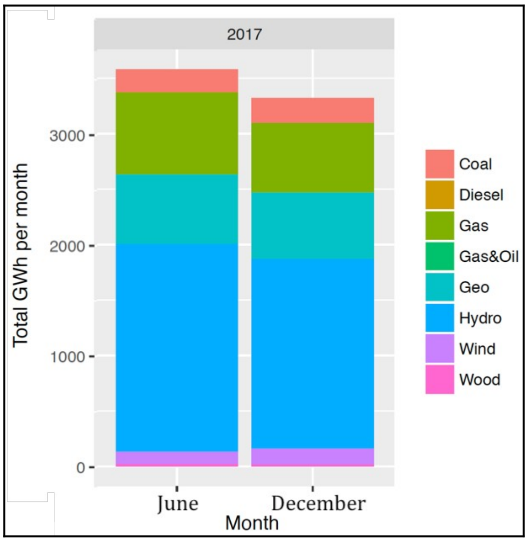


Fig. 2| Total electricity generation per month

Source: Based on (Anderson et al., 2018).

Fig. 3 illustrates electricity generation by time of day on GWh per half-hour trading period. Times of peak electricity generation are characterised by a higher electricity supply and demand at certain times and occur in early morning and evening hours in winter 2017. The maximum power on an average day in winter 2017 was 6.2 GW (equivalent to 3.1 GWh per half-hour) and 5 GW in summer. Times of electricity peaks change by season. In summer 2017, the evening peak was much flatter and occurred slightly earlier compared to winter of the same year. This change in the electricity supply pattern is caused by weather conditions in December that do not necessitate appliances such as electrical heating systems to be activated, coupled with daylight saving and also longer daylight hours for summer, a lower use of lighting technologies in the early evening.

All figures and calculations in this report consider New Zealand daylight saving.

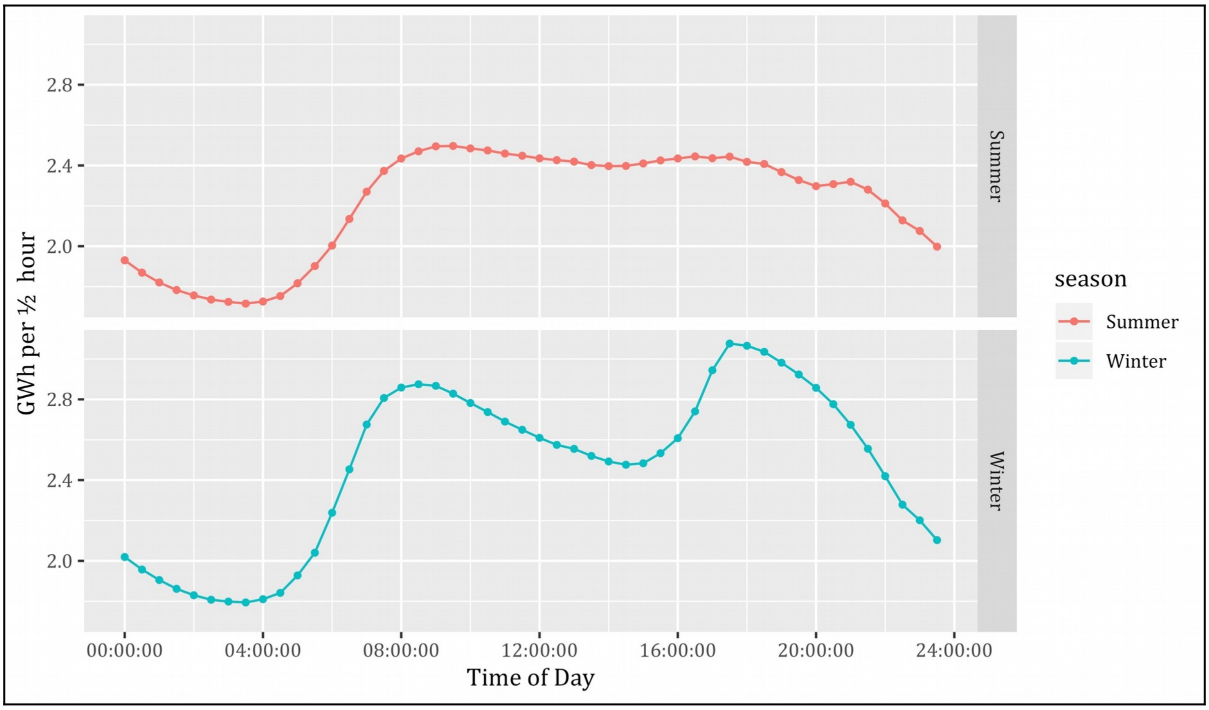


Fig. 3| Daily average half-hour electricity generation profile in summer and winter 2017

Source: Based on (Electricity Authority, 2018c)

Increased demand during time intervals of high electricity demand are largely supplied by hydro electricity generation. Hydro electricity generation as depicted in Fig. 4 represents a significant part of New Zealand's electricity supply and necessitates active monitoring and management (Transpower New Zealand Limited, 2018c). This management considers the storage of hydro for future electricity generation. Hydro capacity management supplies thus electricity of future times. Increasing electricity demand may jeopardise sufficient hydro capacity to meet peak demand and may necessitate supportive fossil-fuel based electricity generation.

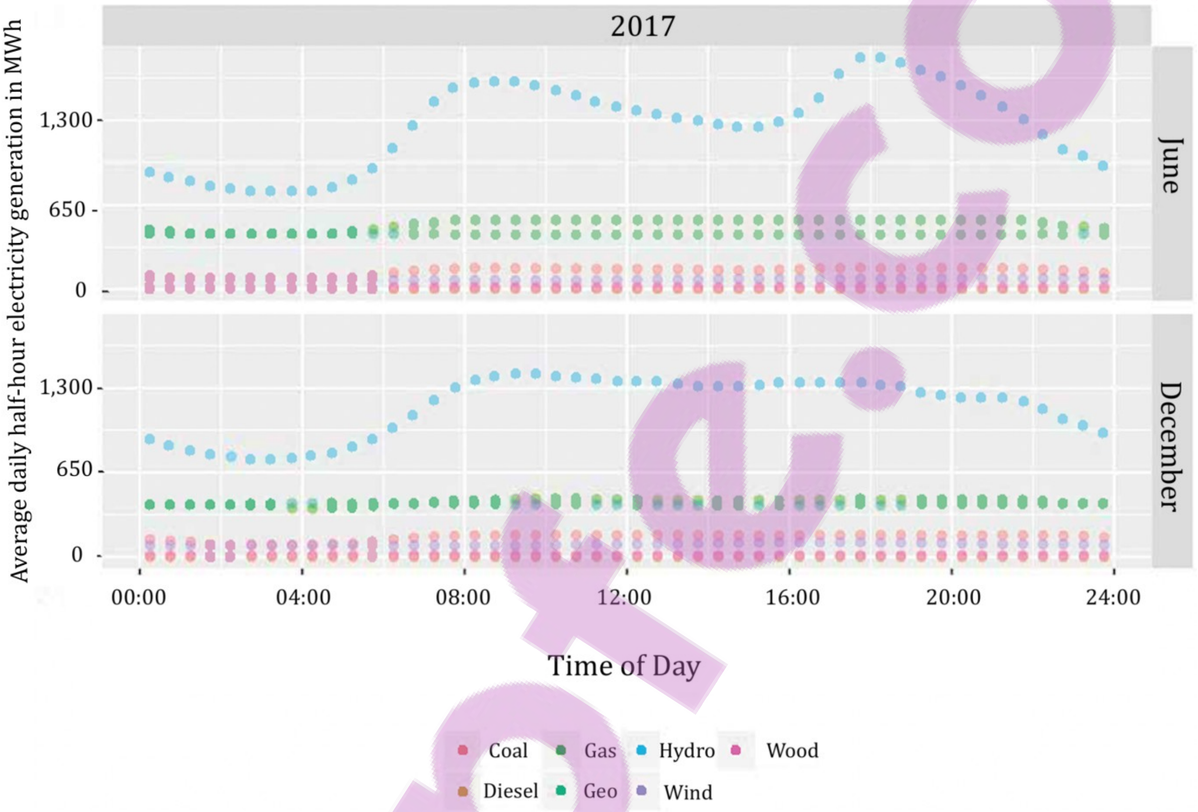


Fig. 4| Average daily half-hour electricity generation profile by sources in June and December

Source: Based on (Anderson et al., 2018).

2.2 Electricity demand

In 2015, electricity consumption in New Zealand was 39,767 Gigawatt hours (GWh) (Energy Efficiency and Conservation Authority, 2017). Compared to the previous year, this is an increase of 1.5%.

Fig. 5 portrays the total electricity demand by end use for 2015 in GWh. Aluminium Manufacturing (16%), Motive Power (14%), Refrigeration (13%), and Water Heating

(12%) encompass more than half of the utilised electricity. This is followed by Lighting (11%) and Space Heating (10%) (Energy Efficiency and Conservation Authority, 2017).

Fig. 6 extends this perspective and depicts the total electricity demand by sector for 2015. Households in New Zealand represent 31% of the total nation-wide electricity consumption, followed by Primary Metal Production and Manufacturing (16%), and then Dairy Cattle Farming (5%).

Fig. 7 shows the estimated electricity consumption by different household appliances. This shows high domestic electricity use in refrigeration, water heating, lighting, and space heating.

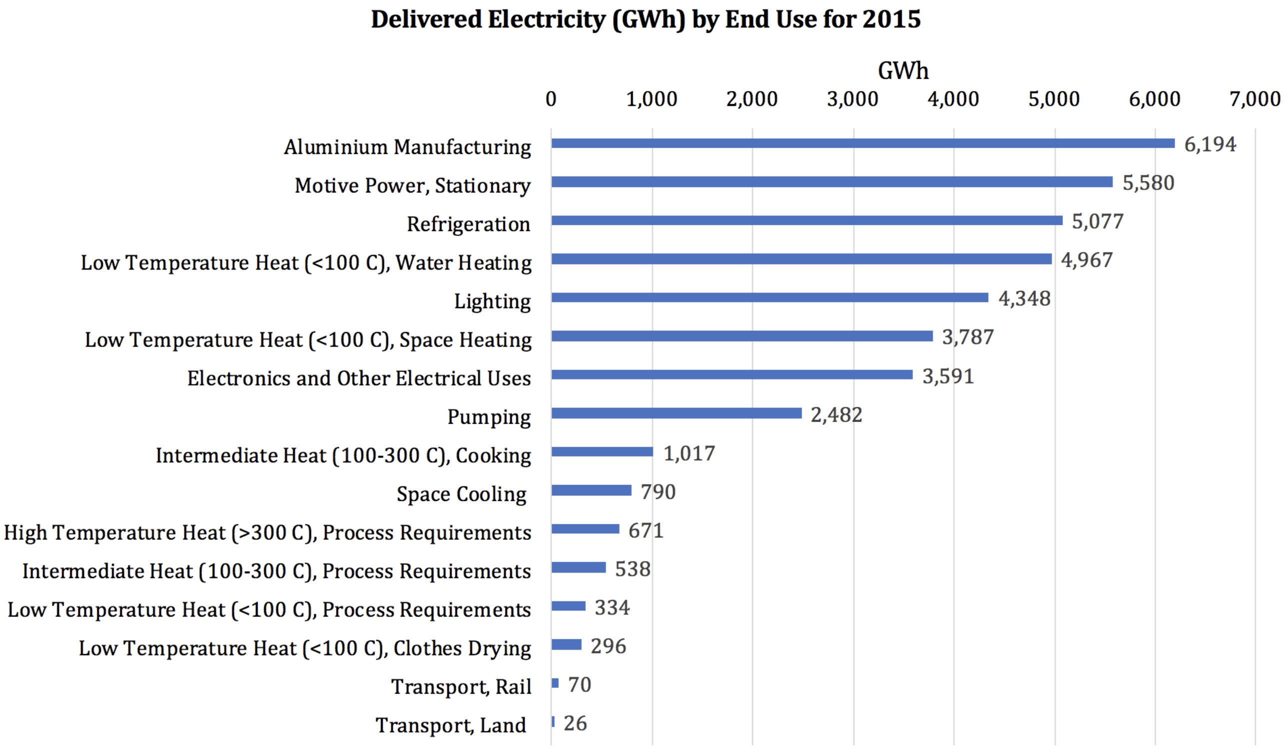


Fig. 5| Total electricity demand by end use for 2015

Source: Based on (Energy Efficiency and Conservation Authority, 2017).

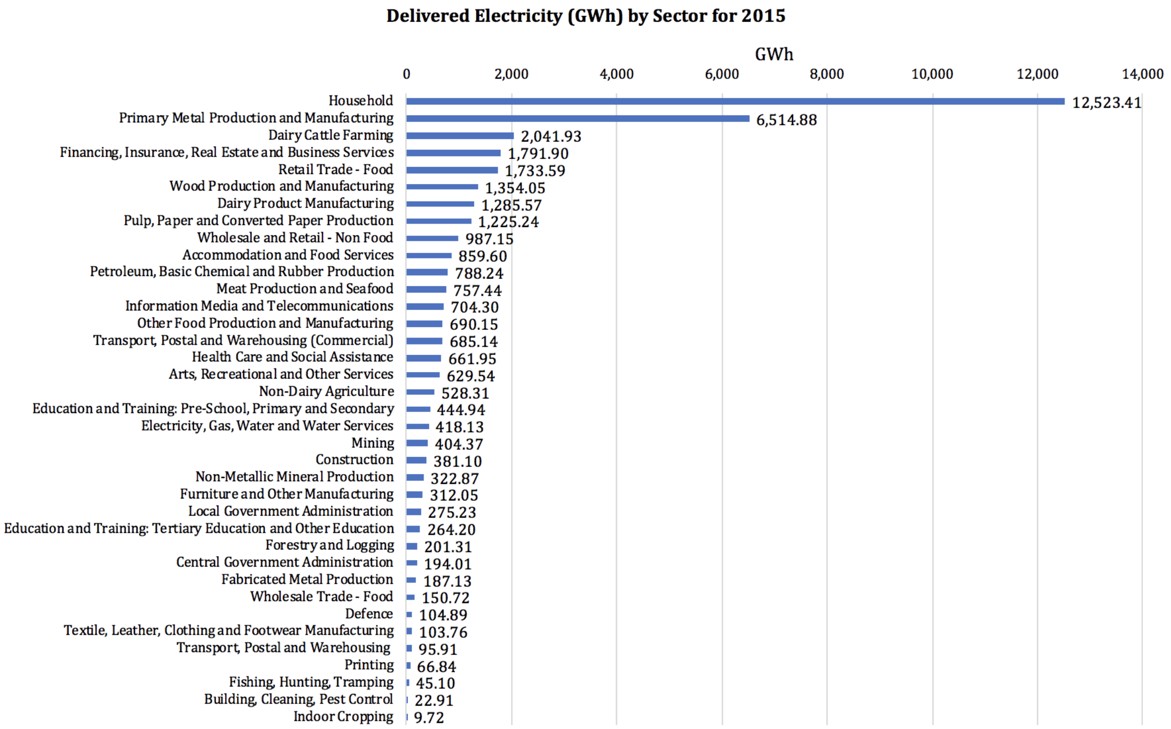


Fig. 6| Total electricity demand by sector for 2015

Source: Based on (Energy Efficiency and Conservation Authority, 2017).

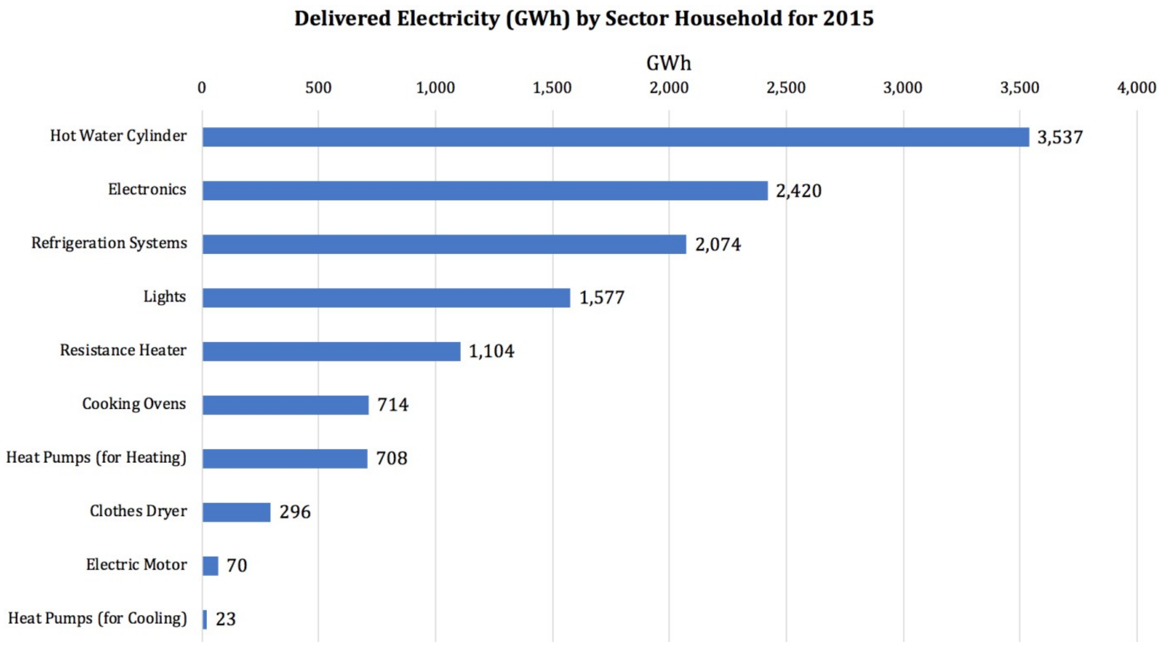


Fig. 7| Total electricity demand by technology in sector household for 2015

Source: Based on (Energy Efficiency and Conservation Authority, 2017).

In 2015, hot water cylinders in residential households accounted for 28% of the total electricity consumption. “Electronics” is a group of miscellaneous appliances that cannot be associated to other groups. We identify Refrigeration Systems (17%) and Lights (13%) as technologies with high electricity consumption. Heat Pumps, in this context, account for six per cent of the total electricity consumption in the household sector which was less than initially expected.

From the DR perspective, residential hot water heaters, refrigeration systems and heat pumps have DR potential since interrupting these appliances does not immediately lead to an impact on service that would occur when interrupting lighting technologies. These appliances have the ability to execute their individual purpose even when the electricity supply is interrupted due to the ability of heat (or cold) to be stored for a period of time. The analysis in this paper will therefore focus on these three appliance groups that have storage ability and also have a significant energy consumption.

Summarising the electricity demand landscape in New Zealand, households utilise the most electricity by sector and notably appliances with a storage ability such as hot water systems, refrigeration systems and heat pumps are major uses. We can clearly identify two distinctive daily peaks in winter, and a comparatively much flatter evening daily peak in summer.

Peak demand in New Zealand is met by hydro and to a smaller extent by gas electricity generation. This is in stark contrast to many other countries where peak demand is met by fossil fuel generation for example in Germany and the United Kingdom. Because of this the carbon intensity of electricity generation has no strong connection between peak-demand time periods and carbon intensity in NZ (Khan, Jack, & Stephenson, 2018). However, hydro storage in New Zealand is dependent on seasonal environmental conditions and as electricity demand grows, in the future it may not have the capacity to meet demand peaks.

3 Categories of DR in New Zealand

The New Zealand electricity market currently contains a variety of DR mechanisms such as ripple control (RC), spot market pricing, curtailable load strategies, and instantaneous reserves (Electricity Authority, 2015; Strahan, 2014). These mechanisms provide DR at different timescales. Historical, current and potential future DR mechanisms across different timescales are summarised in Fig. 8 and Table 1 and depicted by individual indices.

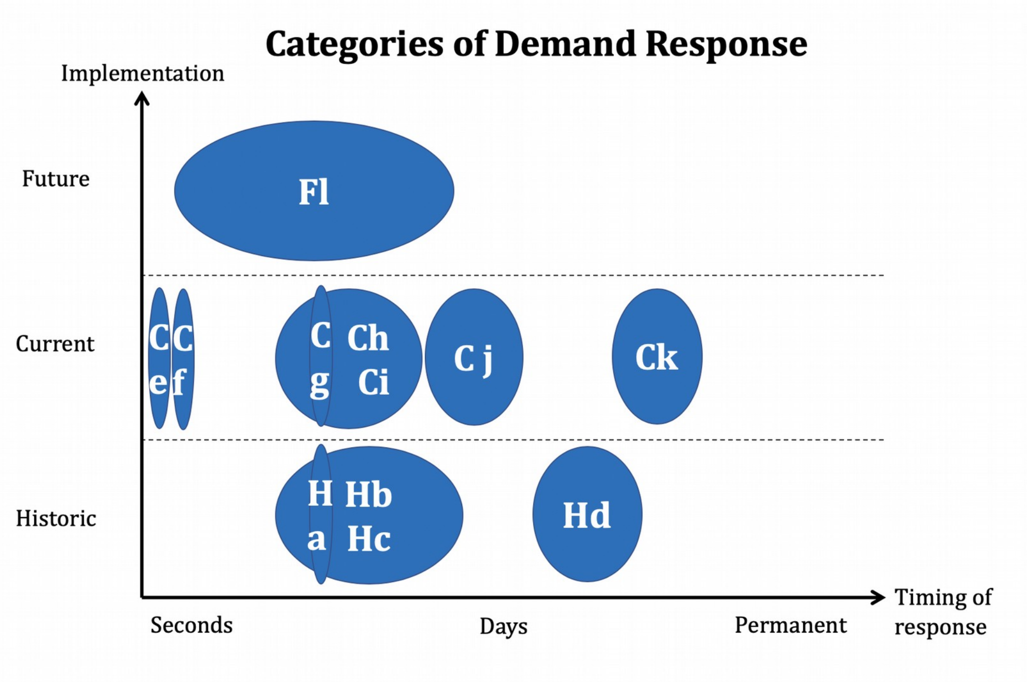


Fig. 8| Categories of DR

Source: Based on (Strahan, 2014).

Table 1: Categories of DR - explanation

Implementation index	Forms of demand response in the NZ electricity sector	Timing of response
Ha	Industrial consumers responding to spot price	30min
Hb	Distributors using ripple control	Minutes, hours
Hc	Providing interruptible load into instantaneous reserve market	Minutes, hours
Hd	Domestic consumers reducing consumption during conservation campaigns	Weeks, months
Ce	Interruptible load – Fast Instantaneous Reserve	Second
Cf	Interruptible load – Sustained Instantaneous Reserve	Seconds
Cg	Spot market pricing for domestic customers (Flick Energy)	30min
Ch	Increased availability of peak/off-peak tariffs for domestic consumers	Minutes, hours
Ci	Projects (EA's dispatchable demand, EA's DSBF project, Transpower's demand response programme)	Minutes, hours
Ck	Curtailable load	Hours, day
Ck	Seasonally varying prices (Powershop)	Months
Fl	Introduction of smart appliances und use by households and businesses	Minutes, hours

Source: Based on (Electricity Authority, 2015; Strahan, 2014).

The spot market in New Zealand is an essential part of real-time DR programs through representing altering electricity spot market prices based on electricity supply and electricity demand. Here we explore one example of real-time pricing in connection to DR. Twenty-five electricity retailers operate in New Zealand (May, 2018) and build a competitive market environment. Competition between retailers leads to the development of business models. These business models are based on the foundation of an unbundled electricity market. In New Zealand, ownership unbundling in the electricity market separates former vertically integrated energy companies and, amongst other effects, enables customers to change their electricity retailer and (Ministry of Business, Innovation & Employment, 2010). Industrial and more recently residential electricity consumers are able to respond to time-of-use electricity price signals. Spot market energy volumes in New Zealand are traded every thirty minutes. They allow electricity consumers to buy and utilise electricity during times when the price for one unit of electricity (e.g. MWh) is lower than during times of a high level of electricity demand. Fig. 9 and Fig. 10 illustrate the relationship between electricity demand (in New Zealand equivalent to electricity generation) and increasing electricity prices for summer and winter 2017. Electricity peaks are clearly visible in both Islands. In summer, only one peak exists while the winter electricity demand is characterised by two clearly visible peaks. The first peak in both seasons occurs at approximately 09:00 (trading period 18), the second peak in winter at 18:00 in the evening (trading period 36). As can be seen, electricity prices on the spot market follow a similar trend to electricity demand but are often more volatile, particularly at evening trading periods.

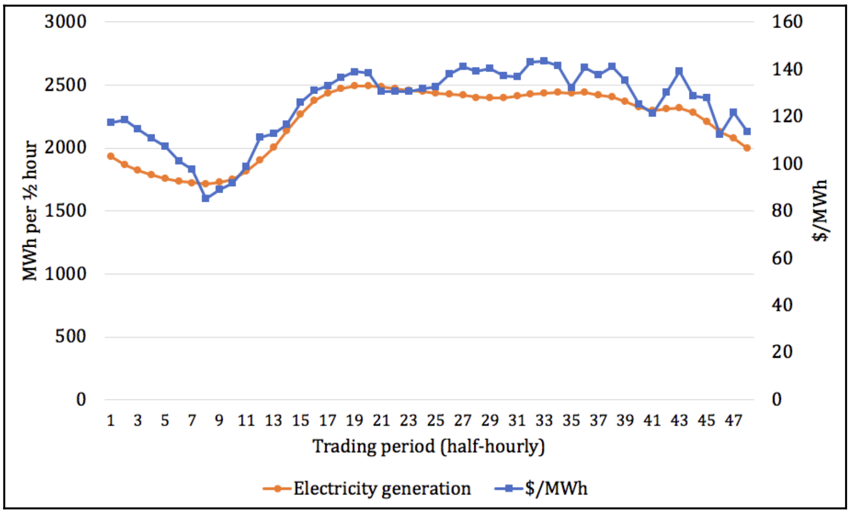


Fig. 9| Daily average electricity generation and spot market price profile for summer 2017

Source: Based on (Electricity Authority, 2018b, 2018e).

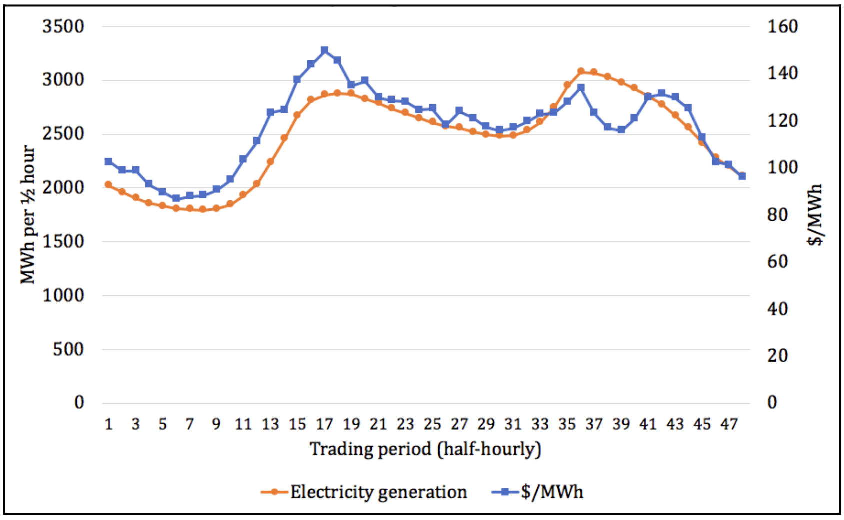


Fig. 10| Daily average electricity generation and spot market price profile for winter 2017

Source: Based on (Electricity Authority, 2018b, 2018e).

DR in New Zealand has developed over time and has evolved with legislation and progress in technology. The following sections elucidate a variety of DR mechanisms in New Zealand.

3.1 Critical Peak Pricing

One approach to capture costs of network contingencies is described in congestion period demand (CPD) charges, also referred to as control period demand. These charges occur at times when the electricity system (electricity generation, transmission lines, or distribution lines) reaches its maximum load and generates stress on the utility grid. To try and reduce demand during times of peak demand, customers (currently only commercial customers) are charged for demand electricity in dollars per kW. This charge is approximately equivalent to the cost of constructing another kW of capacity (Jack, Ford, Dew, & Mason, 2016). For residential customers this charge is incorporated into lines charges and electricity price per kWh and not separately displayed.

In this report we utilise both time-of-use (incorporated by critical peak pricing) as well as real-time electricity pricing (incorporated by spot market electricity prices) in the analysis to estimate the economic value of residential DR in New Zealand.

3.2 Spot Market Pricing

There is a gradually increasing number of electricity customers in New Zealand that choose to be on an electricity tariff with time-of-use or real-time electricity price component. Such services provided by Flick Electric (real-time pricing), amongst others, enhance the utility grid operationality and highlight the potential of DR mechanisms in New Zealand (Electricity Authority, 2018d).

Residential consumers have only recently had the opportunity to buy electricity based on spot market prices, while industrial electricity consumers had this opportunity for much longer. Since 2014 the electricity retailer Flick Electric Co has provided a retail service for residential and business customers that incorporates spot market electricity prices at the residential and business customer's end (Flick Electric Co., 2018a). Participating consumers are required to install a smart meter at their property to allow real-time information of electricity supply and demand to be transmitted to the retailer. To facilitate this data transmission, Flick Electric Co. supplies electricity consumers with a mobile application to monitor the current spot market electricity price developments and further services to design spot market pricing comfortable and practicable for customers (Flick Electric Co., 2018b). Purchasing electricity directly from the spot market encourages a reduction of electricity usage during times that are characterised by a high electricity demand and a high spot market electricity price. In contrast to electricity tariffs with a fixed electricity price, this describes a tariff approach with a time-of-use component.

3.3 Ripple Control

Ripple Control (RC) is a historical and widely utilised form of DR in New Zealand. Installed in the 1950s as a measure of controlling load during intervals of low hydro electricity generation, RC partially cuts off load at the customer's premises (especially hot water systems) and thus enhances the balance of electricity supply and electricity demand (Ministry of Business, Innovation & Employment - New Zealand Smart Grid Forum, 2015). Via the electricity distribution system, a frequency signal is received by ripple receivers and initiates load curtailment until a second signal enables the appliance's operation again. RC provides lower electricity charges for customers but requires the consent of customers to cut load at certain times, which are not announced prior to the DR event. RC is also utilised at fixed times to switch street lights on and off. It is furthermore used to facilitate electricity tariffs aiming to switch from day- to night-tariffs.

Development in the electricity system in the last seventy years has changed the use and extent of RC in New Zealand. In 2006 RC transmitters were owned by twenty-seven different owners, most of which were lines companies. Consumers, especially based in the North Island, have partially switched to gas water heating and do not use electricity for water heating. Load control programmes such as Transpower's DR programme, Instantaneous Reserve (described in more detail below), and RC compete with each other and lead to a decreasing need for RC. Some smart meter technologies also have the capability to control load but these are not necessarily owned by the same company that currently manages the RC receiver and this has led to an uncertain situation where the task of load control is not clearly defined (Ministry of Business, Innovation & Employment - New Zealand Smart Grid Forum, 2015). In addition, RC has a maximum controllable load of 880 MW and transmitting plants are over twenty-five years old and becoming increasingly unreliable (Underhill, 2006). While RC continues to be used in New Zealand, approaches to maintenance und upgrading of RC infrastructure and the extent of usage regionally differ and influence the capability of RC to be successfully operated (Ministry of Business, Innovation & Employment - New Zealand Smart Grid Forum, 2015).

3.4 Load curtailment and load shifting

Other forms of DR are curtailable load and load shifting, respectively. A minimum customer size (kilowatt) is required to participate in curtailable load tariffs. Two forms of curtailable load are prevalent. The first form curtails an electricity load while the second form curtails the load only to a specific, predetermined level (Aalami, Moghaddam, & Yousefi, 2010). Fig. 11 demonstrates the second form of curtailable load where the initial load is curtailed to a predetermined level of approximately five-hundred kilowatts over nine hours.

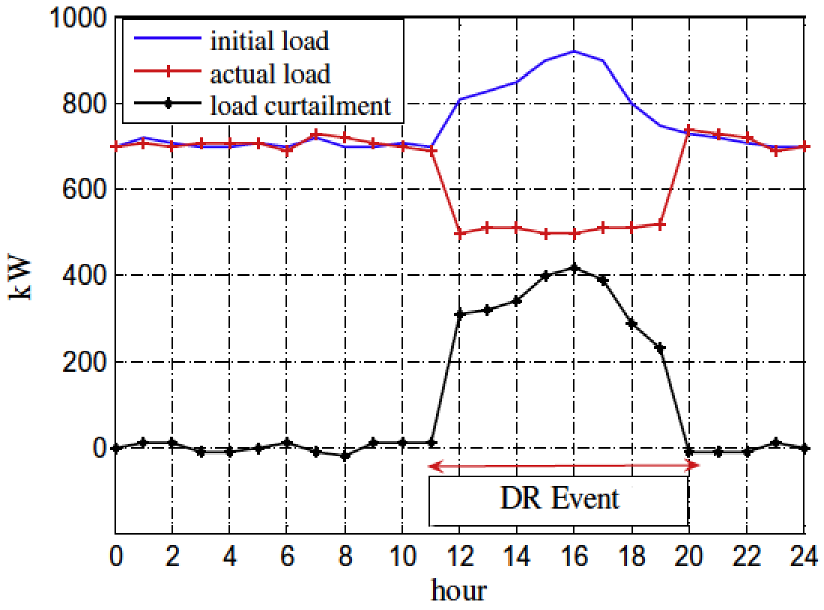


Fig. 11| Load curtailment during DR event

Source: (Chakrabarti, Bullen, Edwards, & Callaghan, 2012).

Effects of load curtailment in the context of DR are described in (Palensky & Dietrich, 2011).

In contrast to energy efficiency that permanently reduces electricity consumption by upgrading appliances or incorporating electricity saving measures, DR, especially the curtailment of load over a longer time, has the potential of generating a rebound effect in the electricity consumption pattern. In the following we use the example of heat pumps in winter season to clarify this effect.

Thermostatically controlled electricity-based heat pumps in winter attempt to maintain a certain temperature in residential households. While the heat pump is likely to operate at a level of e.g. fifty per cent once a predetermined temperature setting is reached, disengagement of the appliance and therefore temperature reduction of the space will lead to a higher electricity consumption once the appliance is turned on again. Instead of preserving a temperature level, there is now the need to overcome the difference between actual room temperature and predetermined temperature setting. The operation level could increase and if so, uses relatively more electricity compared to an appliance operation with no load interruption. Fig. 12 demonstrates this phenomenon where DR with load curtailment generates a second peak in electricity consumption and shows that DR does not necessarily lead to a lower electricity consumption but influences the electricity consumption pattern (Palensky & Dietrich, 2011). In contrast, energy efficiency is depicted in the dotted line and reduces electricity in general without taking variable conditions into account.

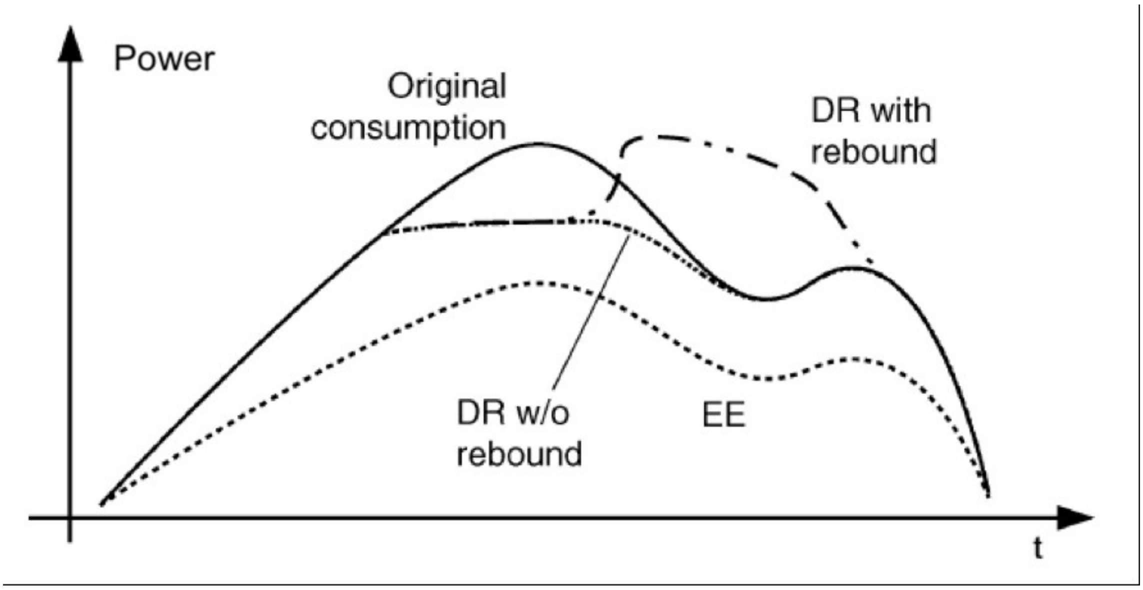


Fig. 12| DR with rebound effect

Source: Based on (Palensky & Dietrich, 2011).

3.5 Transpower DR programmes in New Zealand

Since 2007 Transpower has conducted a variety of DR programmes (Transpower New Zealand Limited, 2018a). Transpower provides a DR programme that, in contrast to curtailable load, allows customers to react voluntarily on a DR signal to reduce electricity consumption. This programme is focused on customers with at least twenty or more kilowatts of peak demand. This indicates that residential households might not be in focus of this programme unless they can provide a community demand aggregation mechanism (Transpower New Zealand Limited, 2018b). Approved customers participating in Transpower's DR programme are informed hours before the actual DR event occurs. During this time interval Transpower and the customer agree on a price and an available kilowatt amount to be reduced during the DR event. In 2013, Transpower's DR programme had 134 MW of industrial customers registered. During this year, twenty DR events were successfully called (Transpower New Zealand Limited, 2014).

Transpower does not determine the mechanism that leads to a reduction in electricity consumption but allows the customer to choose between the usage of stand-by generators, load curtailment, and the utilisation of batteries or alternative sources (Transpower New Zealand Limited, 2018d). In contrast to RC, the DR programme from Transpower extends the way end-users and system operators communicate with each other. Furthermore, this programme does not solely focus on hot water systems or heat pumps but enables a broader approach where the capacity is the decisive parameter rather than the appliance. The information on Transpower's DR programmes extend the view how DR mechanisms could be implemented and facilitate DR scenario development to estimate the technical potential residential DR.

4 Data & Methods

The estimation of the technical potential of residential DR in New Zealand forms the core of this paper. To do this we utilise a variety of data sources and methodologies to estimate both energy and economic potential. This chapter describes these data sources and the methodologies used.

In summary, average seasonal household electricity load profiles for hot water heaters, heat pumps, and refrigeration were derived from existing data. These profiles were scaled to represent the total New Zealand household population and so give 'whole of demand' values. Three DR scenarios were then applied: full load curtailment, halved load curtailment, and load shifting. We conducted calculations for each individual appliance as well as for groups of appliances under these scenarios. These *energy* scenarios were then used to estimate the *economic* potential of DR using data on spot market prices and congestion charges.

The data used were drawn from five core sources:

- Energy Efficiency and Conservation Authority (EECA):
    - Energy End Use Database(Energy Efficiency and Conservation Authority, 2017)
- GREENGrid project:
    - GREENGrid dataset (Anderson et al., 2018)
- Building Research Association of New Zealand (BRANZ):
    - Heat Pumps in New Zealand (SR329)(Burrough, Saville-Smith, & Pollard, 2015)
    - Heat Pumps in New Zealand Houses (CP152)(Burrough, 2010)
    - Energy Use in New Zealand Households (SR155)(Isaacs et al., 2006)
    - Warm, dry, healthy? Insights from the 2015 House Condition Survey on insulation, ventilation, heating and mould in New Zealand houses (SR372)(White & Jones, 2017)
    - Hot water over time – the New Zealand experience (No. 132)(Isaacs, Camilleri, & French, 2007)
- Statistics New Zealand Tatauranga Aotearoa:
    - Households in New Zealand (Stats NZ Tatauranga Aotearoa, 2014a), (Stats NZ Tatauranga Aotearoa, 2014b)
- Electricity Authority (EA):
    - Electricity generation trends (Electricity Authority, 2018c).

The Energy End Use Database from the Electricity Authority was used in section 2 to identify developments in energy consumption in New Zealand. In this section, it was used to compare two methods to estimate the total New Zealand energy consumption for heat pumps, electric hot water heaters, and refrigerators in residential households (See Section 4.2).

Electricity demand profiles of forty New Zealand households serve as the foundation of calculations and were measured by GridSpy monitors in the context of the GREENGrid project (Stephenson et al., 2018). GridSpy recorded electricity power on a one-minute granularity on each power circuit. These demand profiles provide baseline time-of-day load profiles for each appliance by season (See Section 4.2).

The Building Research Association of New Zealand reports on heat pumps and hot water heaters in residential households and the Census 2013 household data were used to scale heat pump and electric hot water appliance demand profiles to the total number of appliances in New Zealand (See Section 4.2).

The Electricity Authority data was used to compare the baseline and DR scenarios with measured overall electricity generation to establish the extent to which the scenarios represent a large change to overall system demand.

4.1 Definition of peak times

Due to the absence of adjacent countries, electricity generation in New Zealand is equal to electricity demand and Fig. 3 of section 2 demonstrates that electricity generation increases at 06:00 in both summer and winter and decreases after 09:00 until 10:00, especially in winter. We define this time interval as morning peak. The evening peak occurs at 17:00 and lasts until 21:00 while the shape of the peak in winter is much more defined than in summer. We therefore define intervals of a daily profile as:

Table 2: Daily time intervals

Time interval	Time
Off Peak 1	21:30-05:59
Morning Peak	06:00-10:29
Off Peak 2	10:30-16:59
Evening Peak	17:00-21:29

It should be noted that each interval is set to the start of the individual half hour. Thus e.g. 10:29 is allocated to the morning peak. The table therefore encompasses twenty-four hours of the day. For simplicity we assume the same number of half-hours for both morning and evening peak and do not distinguish between summer and winter.

4.2 Developing half-hourly baseline demand profiles

The calculations to estimate the technical potential of DR require half-hourly appliance load data as a baseline from which DR scenarios can be calculated. To do this we extracted half-hourly load data for hot water heaters and heat pumps from forty households in the GREENGrid dataset (Anderson et al., 2018) and aggregated them to produce a mean seasonal (average over ninety days) load profile over all households. We then scaled these mean profiles using Census 2013 household counts to estimate the total national energy use for Heat Pumps and Hot Water on a seasonal and yearly basis. Finally, we compared these results with 2015 EECA data on delivered electricity in order to validate the calculations.

The following sections describe this process in detail.

4.2.1 Heat Pumps

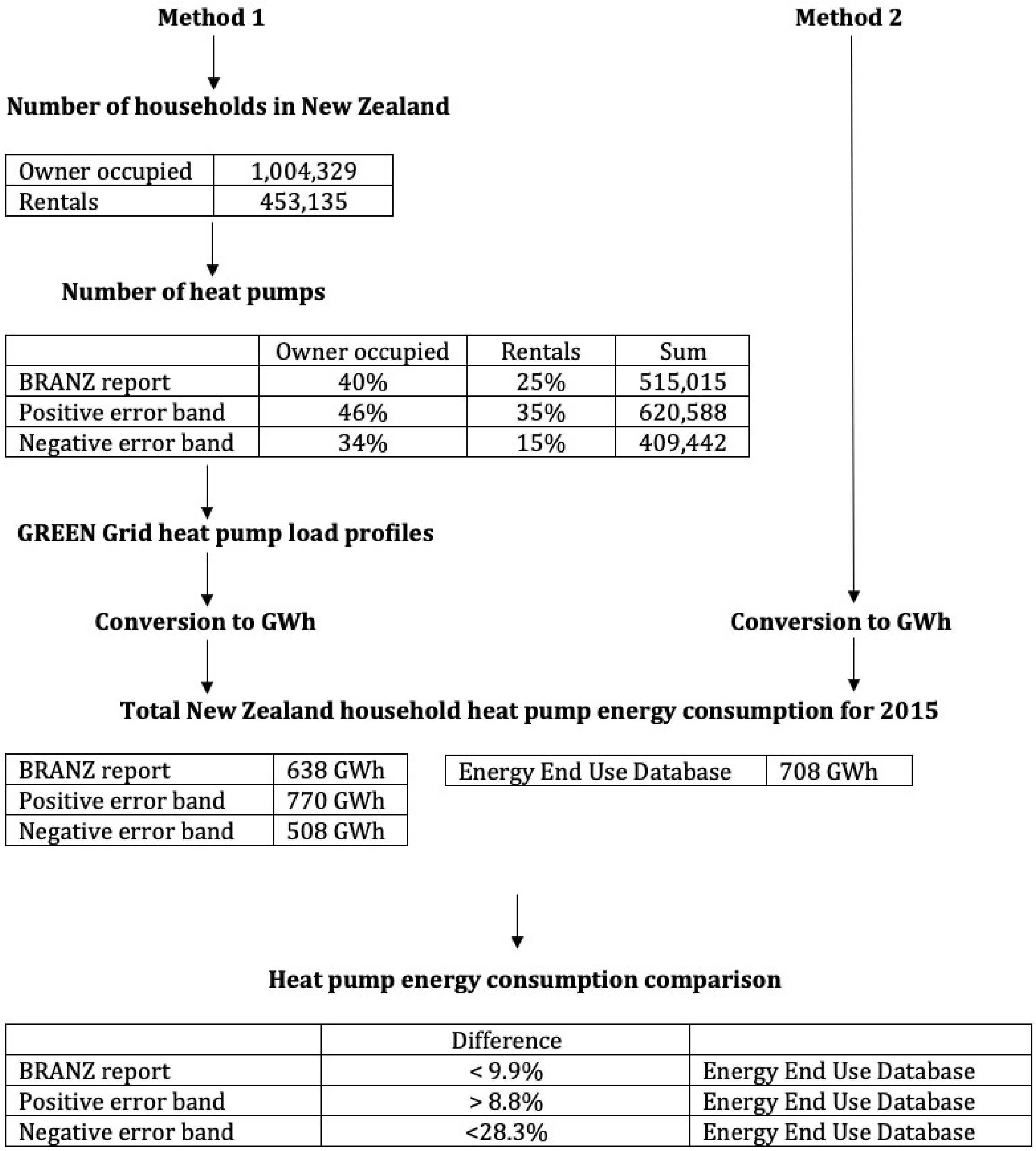
Fig. 13 depicts the comparison of heat pump energy consumption based on

1. BRANZ reports (Burrough, 2010; Burrough et al., 2015; Isaacs et al., 2006; White & Jones, 2017) combined with GREENGrid data (Anderson et al., 2018), Census 2013 data on households (Stats NZ Tatauranga Aotearoa, 2014a, 2014b) and
2. EECA information on delivered electricity (Energy Efficiency and Conservation Authority, 2017).

Method one utilises BRANZ, GREENGrid and Census 2013 data to scale heat pump electricity demand from a one-minute granularity average household profile per season to a total New Zealand profile of average energy consumption per half hour and season. The BRANZ reports distinguish between owner-occupier and rental household tenure and Census 2013 data on the prevalence of such households was used to estimate the number of heat pump appliances in New Zealand. BRANZ information included a margin of error as they were based on survey results conducted in 2010 and 2011. For occupied households the error band was +/-6 % while for rental it was +/-10 per cent. This uncertainty was reflected in our calculations and the effects of using these upper and lower boundaries are shown in Fig. 13.

Method two simply utilises the EECA 2015 total figure of delivered electricity for heat pumps in New Zealand.

As can be seen, method one estimates the total energy consumption per year for heat pumps in New Zealand as 638 GWh and method two suggests a 10% lower energy consumption per year based on the central estimate (638 GWh vs 708GWh) although this may be higher or lower as indicated by the error margins. To prevent overestimation, we utilise the lower total energy consumption estimate (638 GWh) based on the BRANZ reports in subsequent calculations. BRANZ and Census data was recorded before 2015. However, in this analysis we assume that the information provided match with monitored data from 2015.



Method 1

Method 2

Number of households in New Zealand

Owner occupied	1,004,329
Rentals	453,135

Number of heat pumps

	Owner occupied	Rentals	Sum
BRANZ report	40%	25%	515,015
Positive error band	46%	35%	620,588
Negative error band	34%	15%	409,442

GREEN Grid heat pump load profiles

Conversion to GWh

Conversion to GWh

Total New Zealand household heat pump energy consumption for 2015

BRANZ report	638 GWh
Positive error band	770 GWh
Negative error band	508 GWh

Energy End Use Database	708 GWh

Heat pump energy consumption comparison

	Difference	
BRANZ report	< 9.9%	Energy End Use Database
Positive error band	> 8.8%	Energy End Use Database
Negative error band	<28.3%	Energy End Use Database

Fig. 13| Heat pump energy consumption comparison

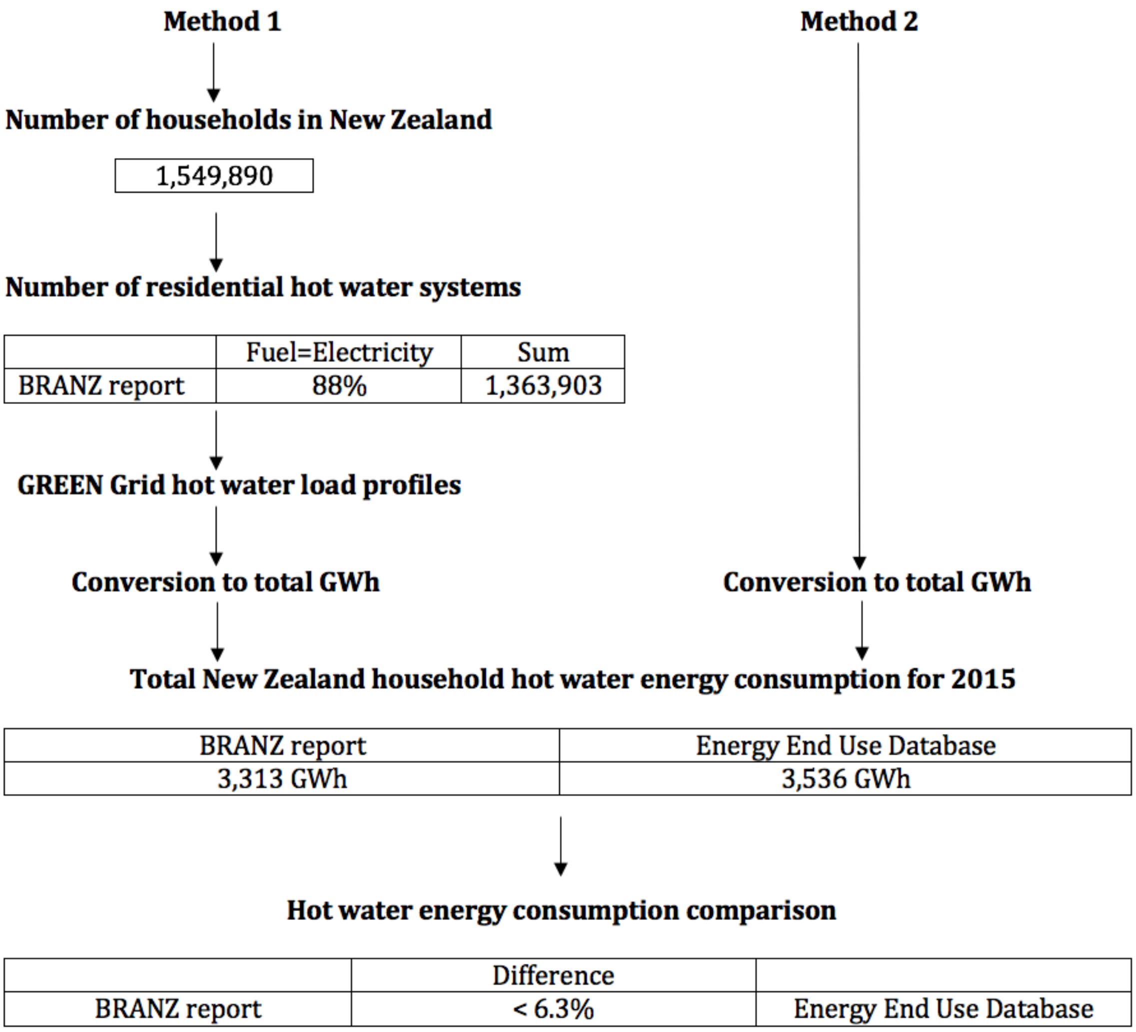
4.2.2 Hot Water

The comparison of hot water heater energy consumption follows the methodology described for Heat Pumps. Fig. 14 compares Method one and Method two based on

1) BRANZ report (Isaacs et al., 2007) combined with GREENGrid data (Anderson et al., 2018), Census 2013 data on households (Stats NZ Tatauranga Aotearoa, 2018) and
2) EECA information on delivered electricity (Energy Efficiency and Conservation Authority, 2017).

However, method one differs from the estimation utilised in the heat pump energy comparison by using BRANZ data on the proportion of electricity fuel-based hot water heaters in New Zealand (88%). In contrast to information on heat pumps, BRANZ reports on hot water heaters do not provide margins of error as they are based on Census data.

After converting the average seasonal daily hot water electricity demand profile from a one-minute granularity to an average seasonal daily hot water energy consumption profile with a half-hour granularity, we scale the energy consumption to the total of New Zealand and compare the figure with the number generated by EECA. We identify a 6% lower energy consumption (3,313 GWh per year) in method one compared to method two. As before subsequent calculations utilise the lower total energy consumption produced by method one to prevent overestimation.



	Fuel=Electricity	Sum
BRANZ report	88%	1,363,903

BRANZ report	Energy End Use Database
3,313 GWh	3,536 GWh

	Difference	
BRANZ report	< 6.3%	Energy End Use Database

Fig. 14| Hot water heater energy consumption comparison

4.2.3 Refrigeration

The GREENGrid dataset does not provide sufficient data to replicate the previous methods to produce refrigeration profiles. Instead, we incorporate a flat energy profile, using the total energy consumption of 2,074 GWh provided by EECA for household refrigerators in 2015. The refrigeration profile, therefore, does not vary during peak and non-peak times but shows a constant profile. In this case we use the Census derived estimates of household numbers in the different tenure types to scale the data appropriately.

4.3 DR scenarios

DR scenarios analysed are based on the DR mechanisms described in section 3 and are calculated based on three scenarios for each load profile and appliance aggregation. We choose simple scenarios to facilitate comprehension of the analysis. Note that we do not consider second order effects such as consequential system price changes under these scenarios but utilise market information measured without the implementation of DR scenarios. Furthermore, we utilise a simplifying assumption under scenario **three** that shifts the load in the prior time-period. This load shifting could involve pre-heating and pre-cooling prior to the time of peak demand. The following section aims to present and describe these three DR scenarios depicted in Fig. 15.

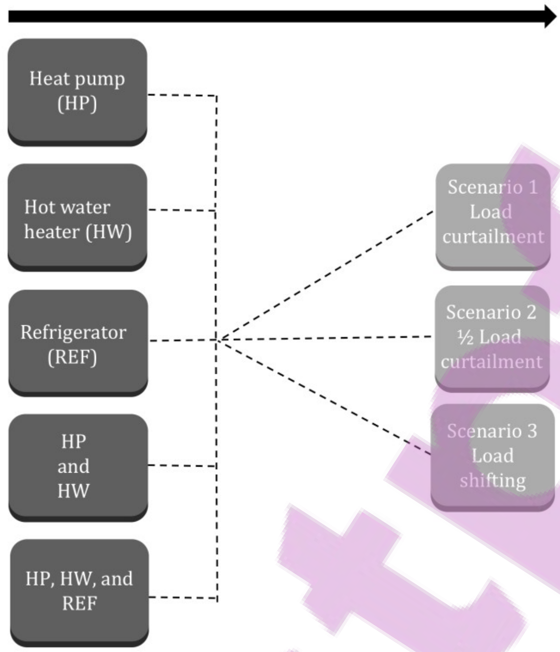


Fig. 15| Appliance and scenario visualisation

4.3.1 Scenario 1: Load curtailment to zero

This first DR scenario assumes a full energy curtailment during times of peaks without any other adjustments in the periods of Off Peak 1 and Off Peak 2. Energy consumption is set to zero at peaks. As mentioned in the introduction, scenarios **one** and **two** are simply used to quantify the demand that can be shifted at peak times and are unlikely to be implemented as they simply reduce load.

4.3.2 Scenario 2: Halved load curtailment

The second scenario is similar to the approach of scenario one but instead decreases energy consumption at peaks until only the half of the original energy consumption is attributed to the newly generated half-hour energy consumption profile in these periods. There are no energy consumption modifications in the time interval of Off Peak 1 and Off Peak 2.

4.3.3 Scenario 3: Load shifting

Scenario three pursues the approach of load shifting. Energy consumption at peaks is shifted to the prior time period of Off Peak 1 or Off Peak 2, respectively. Energy consumption of the individual appliance in the morning peak is attributed to Off Peak 1 while the consumption in the evening peak is incorporated in the interval of Off Peak 2. The amount of energy curtailed at peaks is equally spread over the individual associated off-peak period. This leads to an increase of energy consumption during times of off-peaks while the energy consumption at peaks shows the same pattern as load curtailment scenario one.

Each DR scenario is implemented for each of the four seasons as described in Table 3.

Table 3: Determination of seasons

Season	Definition
Spring	01.09-30.11
Summer	01.12-28.02
Autumn	01.03-31.05
Winter	01.06-31.08

We combine the potential curtailment of each DR scenario with electricity generation data from the Electricity Authority in order to determine the proportion of energy consumption and generated electricity during individual peak times.

4.4 Economic analysis method

In the following, the energy potential of residential DR is connected with its economic potential. DR mechanisms constitute a significant part in the economic analysis and emphasise real-time pricing (spot market) and time-of-use pricing (critical peak pricing in form of CPD charges).

The economic analysis is divided into two parts. The first part highlights the economic value solely based on spot market prices for one year, while the second part incorporates the combination of CPD charges and spot market prices. The analysis comprises data from the following core sources in addition to the sources mentioned at the beginning of chapter 4:

Electricity Authority (EA):
  - Wholesale energy prices (Electricity Authority, 2018a)
- Aurora Energy Limited:
  - CPD charges (Comm. Dev. Mgr., 2018)

Spot market electricity cost are the basis of Fig. 16 and depict the time frame of the 01/09/2016 to the 31/08/2017 and build a one-year database with half-hourly intervals for the following five regions:

- Upper North Island
- Central North Island
- Lower North Island
- Upper South Island
- Lower South Island

As mentioned in Appendix 1: Assumptions, regional differences in energy consumption are neglected in this analysis. Equivalent to the estimation of the energy potential of DR, we build a seasonal average profile of spot market prices (average over all regions) to estimate the economic potential of DR and do not distinguish between regions in the final daily average spot market price per half hour and season.

Fig. 16 portrays average half hour spot market prices for each season and incorporates one year of data on a half hourly basis. Electricity Authority provides price information for five different regions in New Zealand. Spot market prices in spring and summer increase early in the morning until 8:00. The regional price differences are not considerable but on an average day in summer, the Lower South Island represents the lowest prices per MWh. The average maximum price per MWh takes on a value of $50 in both spring and summer.

Autumn and winter constitute generally higher spot market prices than spring and summer. Peak become somewhat identifiable in the average prices per MWh in the morning hours from 07:00 to 09:00, and in the evening hours from 18:00 to 20:00. While there is no distinction of average prices between regions in autumn, differences between regions in winter become visible. The Upper South Island has the highest average price per MWh in winter, followed by the Lower South Island with prices up to $150 per MWh.

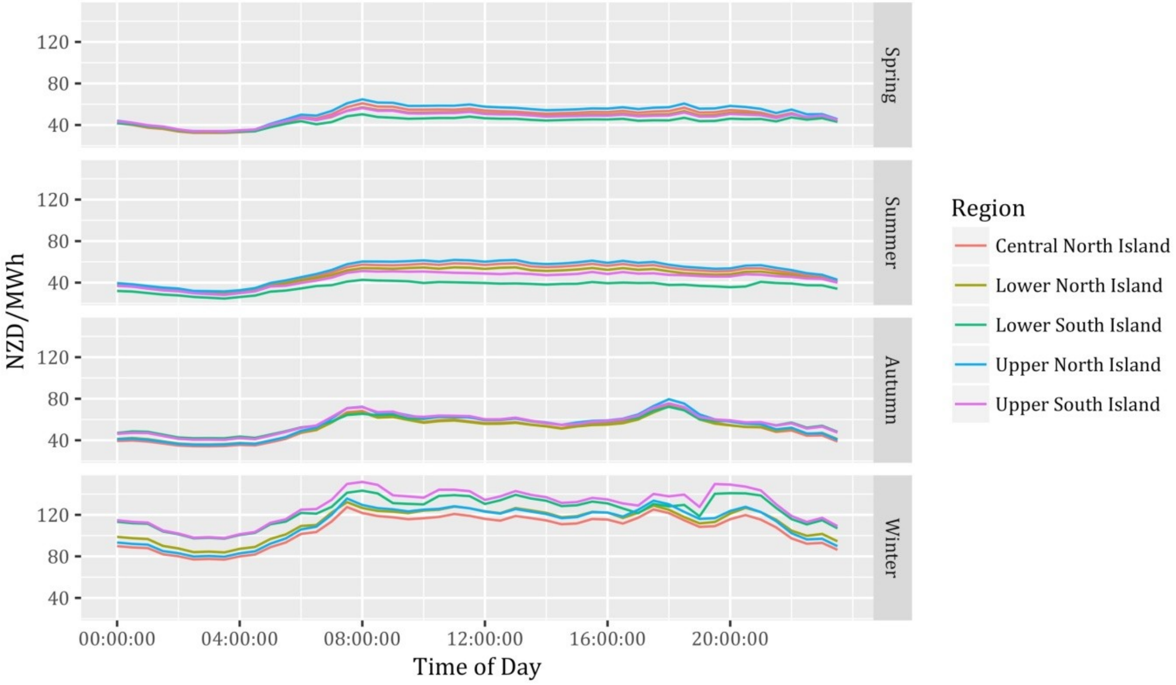


Fig. 16| Average spot market prices

Source: Based on (Electricity Authority, 2018e).

Spot market prices represent only one major component of the total electricity price for customers. Further essential price components are portrayed in CPD charges. The second part of the economic analysis thus considers CPD charges for commercial customers based on data provided by Aurora Energy Limited, as well as spot market prices from the Electricity Authority. As mentioned in section 3.1, CPD charges are currently displayed for commercial customers only. For residential customers, this charge is incorporated into lines charges and electricity price per kWh and not separately displayed. The fact that CPD charges are approximately equivalent to the cost of constructing another kW of capacity allows us to apply these charges on residential customers (Jack et al., 2016).

Aurora Energy provides data of CPD events from the years of 2012 to 2016. CPD events ranged from 1-30 minutes per half hour. We use this information to calculate the probability of CPD events, and, connected with appliance demand data, the average kW of each appliance at CPD. However, due to a lack of data, we do not consider regional variation in these charges. CPD charges are determined by using the following formulas to calculate the **average demand** (in kW) during CPD periods

Equation 1: Calculating $\acute{D}_{CPD}$

$$\acute{D}_{CPD}=\frac{\sum_{j=1}^{j=365}\sum_{i=1}^{i=48} h_{ji} D_{ji}}{\sum_{j=1}^{j=365}\sum_{i=1}^{i=48} h_{ji}}$$

where h_{ji} is the number of CPD hours on the jth day in the half hour period labelled by i and D_{ji} is the demand on the jth day (in kW) in the half hour period labelled by i. Note many of the h_{ji} will be zero as there are only ~100 CPD hours per year. As mentioned in section 5.1 we utilise an average energy consumption profile over each season. In this case, the above equation simplifies to

Equation 2: Calculating $\acute{D}_{CPD}$using seasonal profiles

$$\acute{D}_{CPD}=\frac{\sum_{i=1}^{i=48}\left(H_i^W D_i^W + H_i^A D_i^A\right)}{\sum_{i=1}^{i=48}\left(H_i^W + H_i^A\right)}$$

where

Equation 3: CPD hours in autumn

$$H_i^A=\sum_{j=A} h_{ji}$$

Equation 4: CPD hours in winter

$$H_i^W = \sum_{j=W} h_{ji}$$

are the number of CPD hours in each half hour interval *i* summed over all the 90 days of the season. In this equation $D_i^A$and D_i^W are the average demand (in kW) in each of the 48 half hour intervals for the autumn and winter profile, respectively. Note that we have only included autumn and winter in this sum as we have assumed that the CPD hours in all other seasons are zero. This assumption is supported by Aurora data takes monitored CPD events from 2012 to 2016 into account (Mason, 2018).

Another approach of calculating $\acute{D}_{CPD}$ incorporates the probability of CPD events. In this approach Equation two becomes

Equation 5: Calculating $\acute{D}_{CPD}$using seasonal profiles and probability of CPD

$$\acute{D}_{CPD} = \sum_{i=1}^{i=48} \left(P_i^W D_i^W + P_i^A D_i^A \right)$$

where

Equation 6: Probability of CPD in autumn

$$P_i^A = \frac{H_i^A}{\sum_{i=1}^{i=48} \left(H_i^A + H_i^W \right)}$$

Equation 7: Probability of CPD in winter

$$P_i^W = \frac{H_i^W}{\sum_{i=1}^{i=48} \left(H_i^A + H_i^W \right)}$$

are the fractions of time when the CPD periods occur in the ith interval in autumn and winter, respectively. As the timing of the CPD events vary per year we calculate H_i^A and H_i^W by taking an average over the years of 2012 to 2016 from data provided by Aurora Energy.

The final CPD annual charges are calculated by multiplying the average CPD period demand $\acute{D}_{CPD}$ by the networks CPD rate in $/kW/year. CPD prices are provided for an average kW during CPD per day. We have chosen four different price scenarios consisting of relatively low prices to prevent overestimation. We then scale daily charges to the annual figure. Further details of these calculations can be found in Appendix 2 and Appendix 3. All calculations were separately programmed in R Studio.[1]

The probability of CPD events is crucial to calculate the average kW at CPD events. In the following the methodology in the New Zealand context is elucidated. Note that the Aurora data of CPD in the years 2012 to 2016, shows no CPD events in spring or summer. We therefore assume that the probability of CPD in spring and summer is zero. The x-axis of Fig. 17 constitutes time of day for autumn and winter. On the y-axis, the probability of CPD events for an average day in each season is depicted for every 30 minute period of the day. In both autumn and winter, the probability of CPD events increases during times of peaks. We identify a higher probability and longer duration of CPD events in the winter morning peak than in the winter evening peak. The morning peak in winter attains a CPD probability of 17%, the morning peak in autumn 6%. The probability of CPD events does not display the duration of the individual event but further calculation extends this analysis below.

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[1] The code is available on request. Email: carsten.dortans@web.de

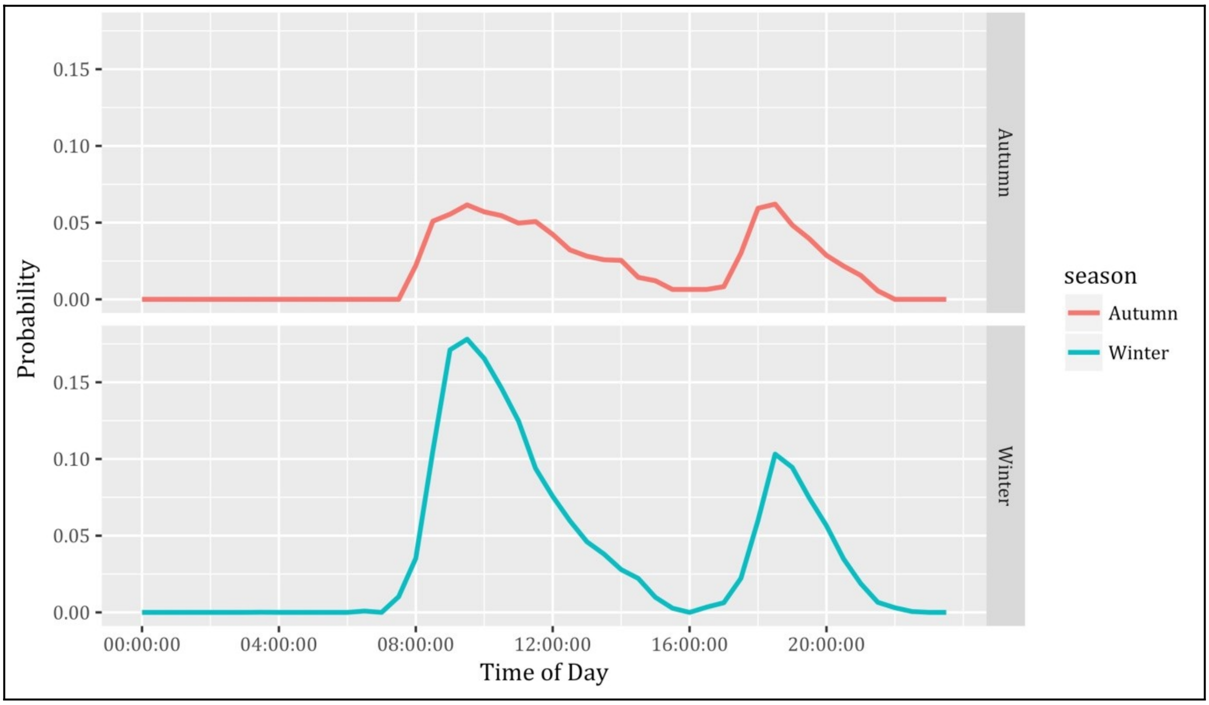

Fig. 17| Probability of CPD events based on Aurora data of CPD in the years 2012 to 2016 of every 30 minute period of the day

Fig. 18 shows the duration of CPD events on a half hourly basis for autumn and winter. The average sum of CPD minutes per half hour and season over the analysed five years of CPD data was multiplied with the individual half hour probability of CPD events. This enables a visualisation of total average CPD hours per half hour and season over the five analysed years. The average duration of CPD events in autumn takes on a value of fourteen hours. The average duration in winter is approximately six times longer, accounting for eighty-two hours in total per year. The average maximum duration of CPD events reaches eight hours in the half hour associated to 09:00 to 09:30. Fig. 17 and Fig. 18 build the connection between peaks and occurrence of CPD events, and underline the potential DR has to decrease stress on the utility grid.

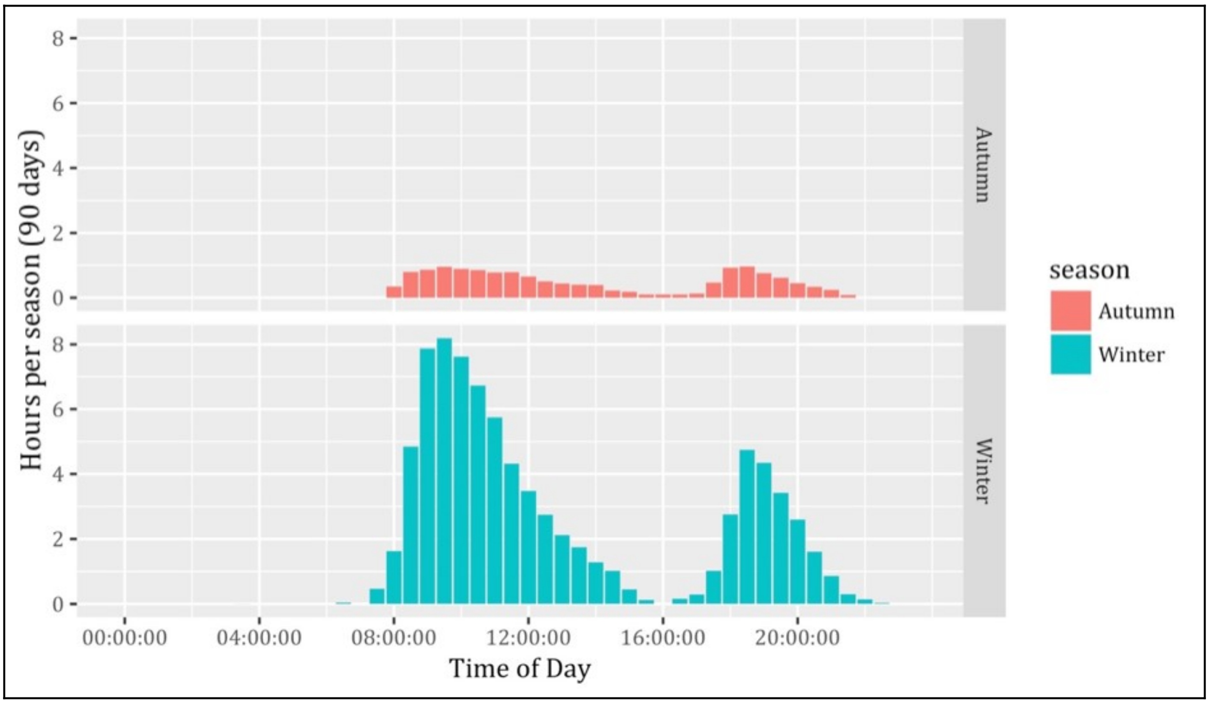

Fig. 18| Total duration of CPD events for autumn and winter

In order to not overestimate economic value, the lowest CPD price of $112.38 per kW per year (Comm. Dev. Mgr., 2018, p. 40) and the average probability of occurring CPD events over the four years for every half hour is used in the calculation of the economic potential of residential DR.

5 Results

This section presents the main outputs of our calculations for each scenario and appliance group. Firstly, the energy reduction potential of the 3 scenarios for residential DR is presented. In a second step, we describe the economic value of the scenarios using the methodology described in the previous section 4.4.

5.1 Energy potential of DR scenarios

The following sections will present the energy reduction potential of DR scenarios one to three for each appliance. Where appropriate, outputs are clarified with associated visualisations to facilitate understanding. The appendices contain additional graphics and tables that have the potential to enhance the understanding in the analysis.

5.1.1 Heat pumps

Fig. 19 depicts our estimate of the total New Zealand heat pump energy consumption profile for an average day for each season. The different times of peaks are colour-coded. Power is scaled to MWh on the y-axis and presented for each half-hour time interval. The time of day is assigned to the x-axis. MWh per half-hour can be easily converted to MW by multiplying with the factor 2. In the following, MWh per half-hour is utilised.

Most heat pump energy consumption occurs in winter, less consumption is prevalent in spring, summer, and autumn. The morning peak in winter portrays up to 160 MWh per half hour, while the evening peak in winter is slightly smaller with 140 MWh. However, the evening peak persists for a longer time than the morning peak. Off-peaks range from less than 20 MWh per half hour in summer, to 90 MWh in winter. Graphic 2 (p. 93) depicts the seasonal average energy consumption profile for heat pumps and changes the perspective from a per day calculation to a seasonal one scaled in GWh.

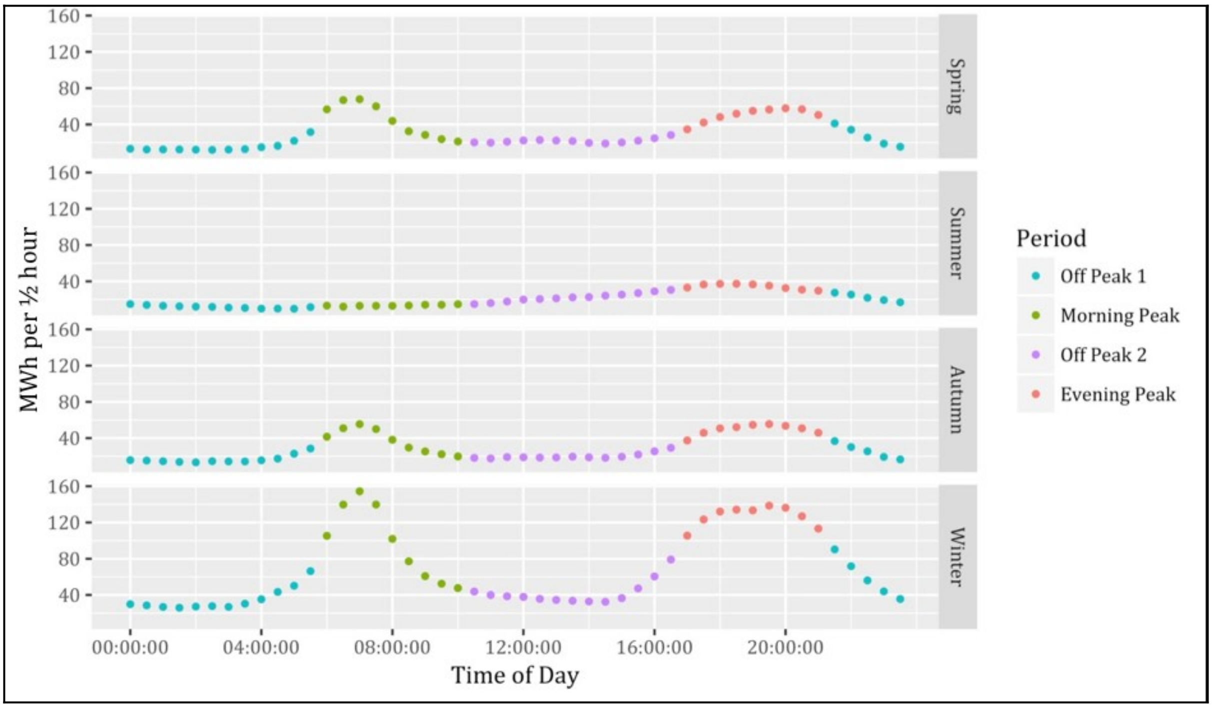

Fig. 19| Estimated daily energy consumption profile for heat pumps

DR scenario one calculates the amount of energy utilised at peaks and sets energy consumption during peaks to zero. Graphic 3 (p. 94) and Graphic 4 (p. 94) clarify this process. The morning peak in winter accounts for an energy consumption of 879 MWh, the evening peak for 1,143 MWh per day. Energy consumption on a summer day is 120 MWh in the morning peak and 308 MWh in the evening peak. The proportion of consumption and total generation in winter is 4% in both morning and evening peak. Graphic 3 (p. 94), Graphic 4 (p. 94), Energy output 1 (p.77) and Energy output 2 (p.77) visualise scenario one for heat pump on a per day and seasonal level.

In scenario **two**, the energy consumption during peak is taken to be half of the energy consumption originally utilised. The potential curtailment during periods of peak demand decreases to 440 MWh per day in the winter morning peak and 571 MWh in the evening peak. Energy consumption in the summer morning peak is 60 MWh and in the evening peak 154 MWh per day. Graphic 5 (p. 95), Graphic 6 (p. 95), Energy output 3 (p.77), and Energy output 4 (p. 78) exemplify this result.

Load shifting in scenario **three** shifts energy consumption during the peak time periods to off-peak periods. The evening peak is shifted to off-peak period two and the morning peak shifted to off-peak period one. Fig. 20 depicts the original and shifted energy consumption for heat pumps per day under this scenario. Graphic 7 (p. 96) and Graphic 8 (p. 96) demonstrate load shifting on a per day and seasonal basis.

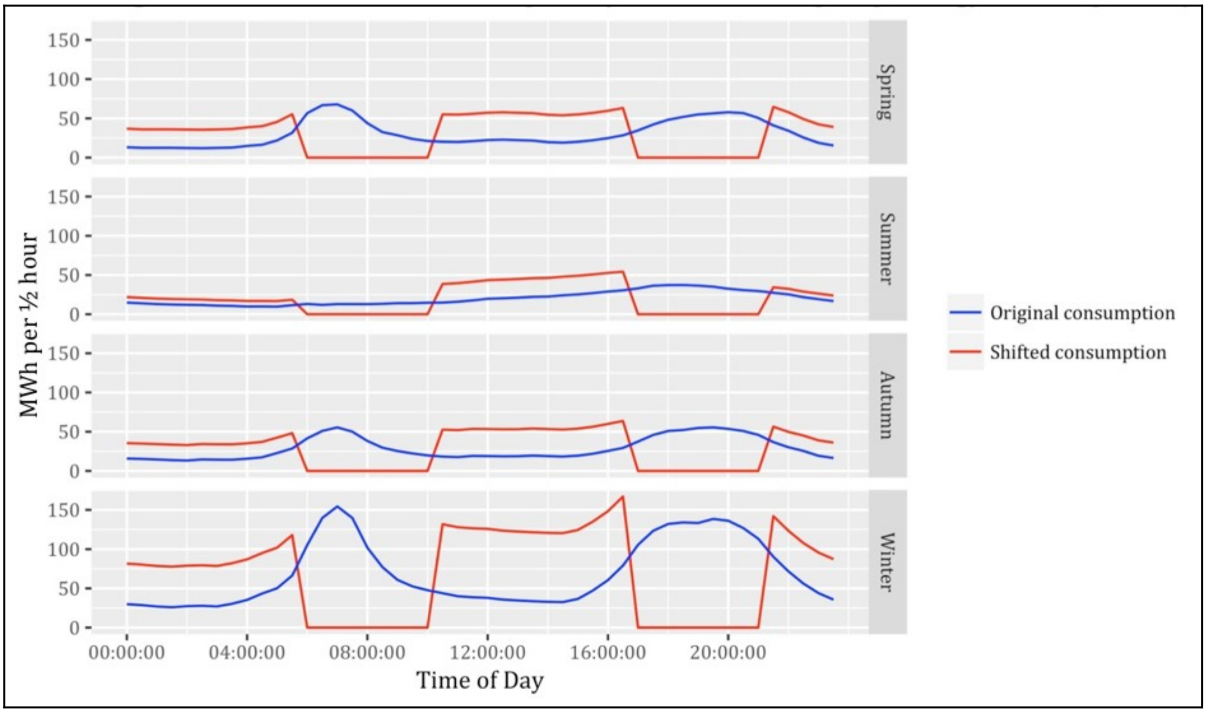

Fig. 20| Estimated daily load shifting profile for heat pumps (Scenario 3)

5.1.2 Hot water heaters

Fig. 21 portrays our estimate of the total average per day energy consumption profile for hot water heaters in New Zealand. This shows a much higher energy consumption than heat pump. Similar to heat pumps, energy consumption of hot water heaters is highest in winter. The morning peak in winter has a peak energy consumption of 520 MWh during a half hour period. Energy consumption during this peak period is more than three times that of heat pumps. The evening peak in winter illustrates a lower energy consumption of up to 350 MWh per half hour. Off peaks range from 80 to 300 MWh per half hour. The differences in energy consumption in the four seasons are not as dramatic as the heat pump.

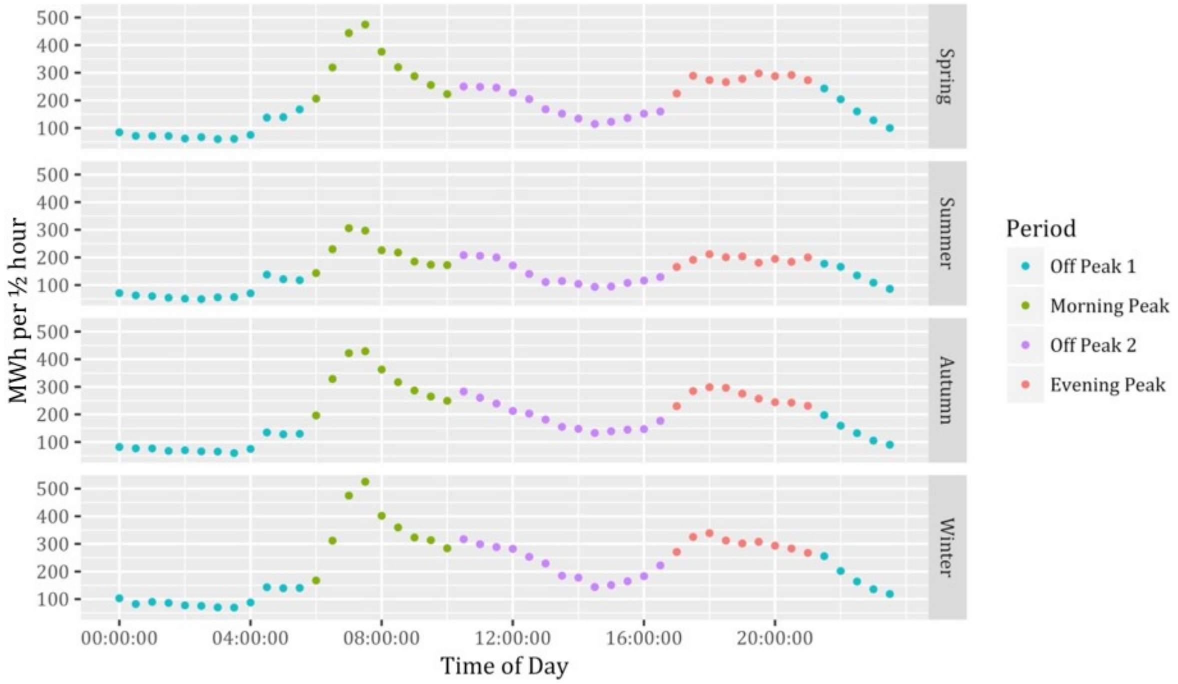

Fig. 21| Estimated daily energy consumption profile for hot water heaters

Load curtailment under scenario **one** results in an energy reduction of 3,160 MWh per day in the winter morning peak, and 1,950 MWh per day in the summer morning peak. This represents 13% of the total electricity consumption of New Zealand during the morning peak in winter, and 9% in the summer morning peak. This is three times that of heat pumps. Graphic 11 (p. 98), Graphic 12 (p. 98), Energy output 5 (p. 78), and Energy output 6 (p. 78) clarify these findings.

Halving the energy consumption during times of peaks under scenario **two** decreases consumption to 1,580 MWh in the winter morning peak per day and to 975 MWh in the summer morning peak per day. Graphic 13 (p. 99), Graphic 14 (p. 99), Energy output 7 (p. 79), and Energy output 8 (p. 79) emphasise these numbers.

Fig. 22 highlights the shifted and original energy consumption of hot water heaters in New Zealand per day under scenario **three**. Compared to scenario one and two this scenario leads to an increased energy consumption during off-peaks. Graphic 15 (p. 100) and Graphic 16 (p. 100) portray further visualisation pertaining to DR scenario three.

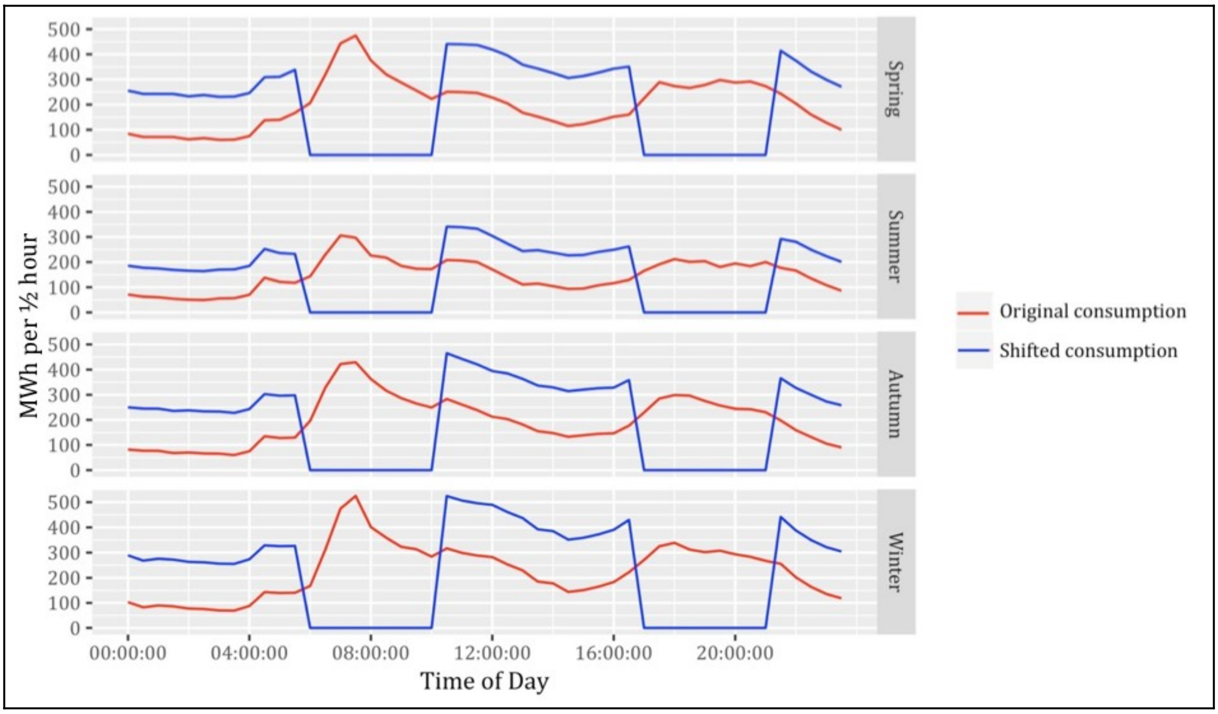

Fig. 22| Estimated daily load shifting profile for hot water heaters (Scenario 3)

5.1.3 Refrigerators

Refrigerators are the third appliance we consider to estimate the technical potential of DR in New Zealand. The energy consumption profile of refrigerators in this analysis incorporates a flat profile. We assume that energy consumption does not change during the day or in between seasons but stays at a consumption of 120 MWh in each half hour and season per day. The amount of energy utilised by refrigerators is between that of heat pumps and hot water heaters. Graphic 17 (p. 101) and Graphic 18 (p. 101) depict the daily and seasonal energy consumption of refrigerators.

Fully curtailed peaks under scenario **one** have a DR energy potential of 1,080 MWh per day and these values can be associated to all times of peaks and all seasons since the energy consumption profile stays the same in each season in our model. This accounts for 4% of NZ's total electricity consumption during times of winter peaks per day, and to 5% in summer. In contrast to the previous appliances, the proportion increases in summer due to the reduction in total energy consumed in that season. Graphic 19 (p. 102), Graphic 20 (p. 102), Energy output 9 (p. 80), and Energy output 10 (p. 80) clarify this result.

540 MWh for each peak time interval per day can be incorporated in the DR potential for halving the energy consumption at peaks under scenario **two**. The proportion of energy consumption and electricity generation in winter decreases to 2% for each peak time interval per day, and to 3% in summer. Graphic 21 p.(103), Graphic 22 (p. 103), Energy output 11 (p. 81), and

Error: Reference source not found (p. Error: Reference source not found) include further visualisation of this scenario.

Fig. 23 depicts load shifting of peaks per day. Energy consumption in off-peak times increases from 120 MWh to 170 MWh and 200 MWh per half hour and day, respectively under scenario **three**. The different duration in off-peak one and off-peak two causes a higher energy consumption in off-peak two than in off-peak one. Graphic 23 (p. 104) and Graphic 24 (p. 104) illuminate load shifting of refrigerator peak energy consumption in addition to Fig. 23.

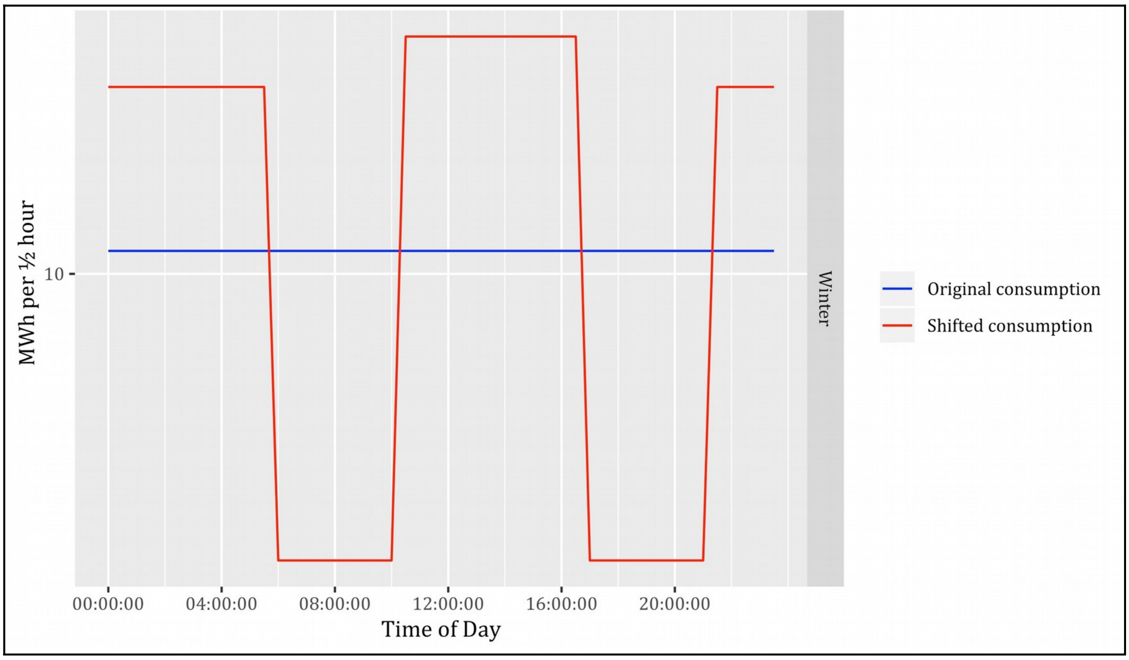

Fig. 23| Estimated total load shifting profile for refrigerators (scenario 3)

5.1.4 Heat pumps, hot water heaters and refrigerators

In this section we explore the DR potential of the combination of all three household appliances.

Fig. 24 portrays the total energy consumption profile for an average day for each season due to the three household appliances. This shows an energy consumption in the winter morning peak of up to 800 MWh per half hour. This represents 14% of New Zealand's total demand during this period. In the evening peak in winter, energy consumption per half hour reaches 600 MWh. Off-peaks vary between 200 MWh per half hour and day in summer, and 500 MWh per half hour and day in the winter. Graphic 33 (p. 109) and Graphic 34 (p. 109) depict the total energy consumption profile for an average day in each season and on a seasonal basis.

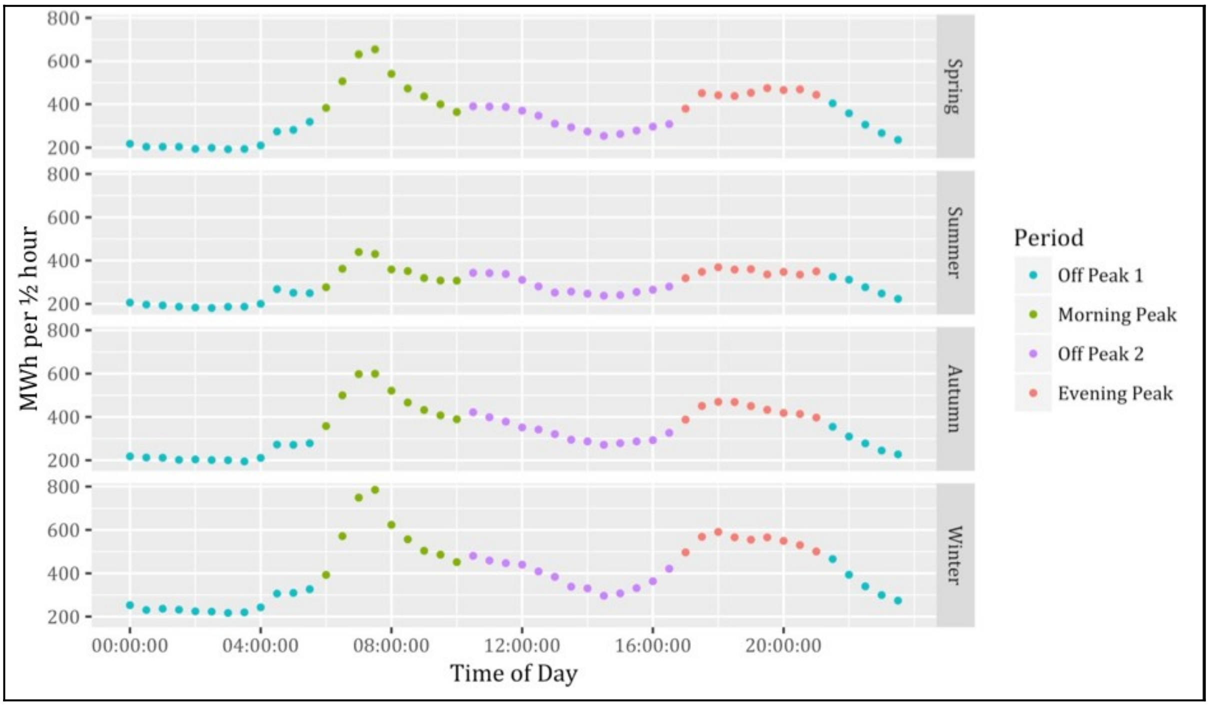

Fig. 24| Estimated total energy consumption profile for HP, HW and REF

Load curtailment (scenario **one**) of all three household appliances at peaks reduces energy consumption by 5,119 MWh per day in the winter morning peak, and 4923 MWh in the evening peak time interval. In the morning this comprises 3,160 MWh for hot water heaters, 1,080 MWh for refrigerators and 879 MWh for heat pumps. In the evening it comprises 2,699 MWh for hot water heaters, 1,080 MWh for refrigerators, and 1,143 MWh for heat pumps. Furthermore, the energy reduction under scenario **one** equates to 3.34 kWh in the winter morning peak, and 3.26 kWh in the evening peak per household.

This is 20% of the total electricity generation in New Zealand during this interval. In the summer, less utilisation of heat pumps decreases this to 15% of total demand in the morning peak period and 14% in the evening. In combination, the appliances modelled could provide a maximum aggregated demand reduction of 1,600 MW in the summer morning peak, and 1,200 MW in the summer evening peak. Graphic 35 (p. 110), Graphic 36 (p. 110), Energy output 17 (p. 83), and Energy output 18 (p. 83) show the per day and seasonal energy consumption profile.

Halving the energy consumption at peaks (scenario **two**) creates a DR energy potential of 2,559 MWh per day in the winter morning peak, and 2,461 MWh in the evening peak. In summer, 1,575 MWh per day can be reduced in morning peak and 1,560 MWh per day in the evening peak. This accounts for 10% of electricity generation in morning peaks in winter and 8% in the summer. Graphic 37 (p. 111), Graphic 38 (p. 111), Energy output 19 (p. 84), and Energy output 20 (p. 84) highlight this development.

Fig. 25 depicts the energy profiles of each appliance, all three appliances and also DR scenario 3. Graphic 39 (p. 112) and Graphic 40 (p. 112) visualise load shifting for an average day in each season and for a seasonal energy consumption profile.

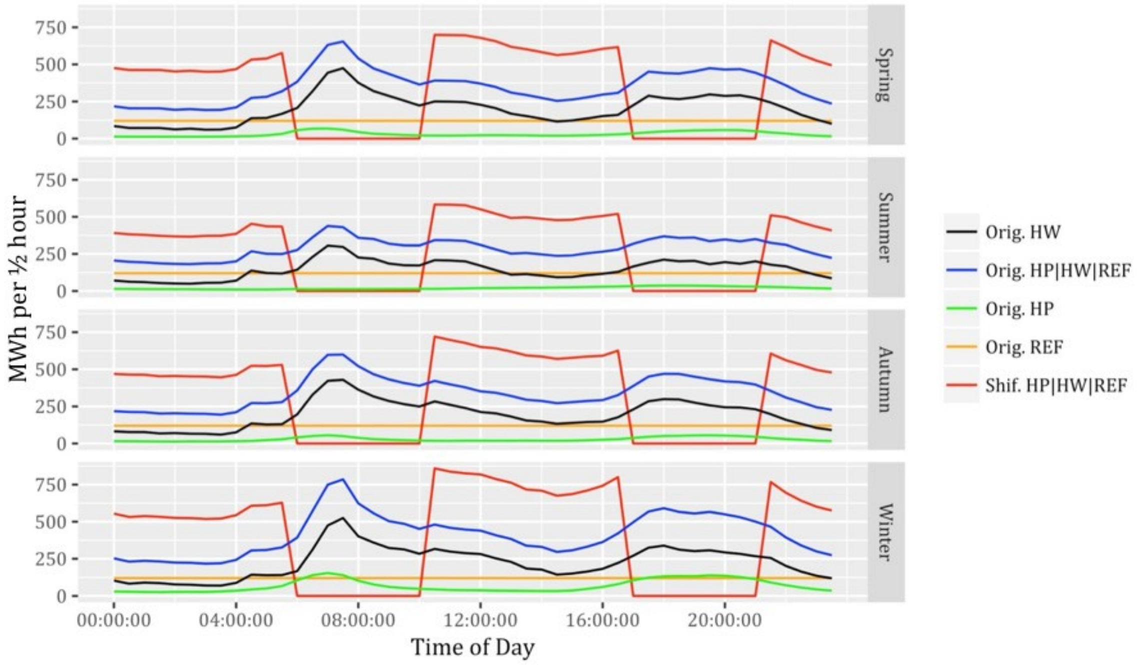

Fig. 25| Estimated total load shifting profile for HP, HW, and REF (scenario 3)

Fig. 26 shows the impact of the DR scenarios on the total electricity daily consumption profile in New Zealand in summer and winter. The blue line depicts the original electricity generation. DR scenarios are portrayed in the colours green (scenario **one**), yellow (scenario **two**), and red (scenario **three**). This figure presents a visualisation of the DR potential of these residential appliances relative to total demand.

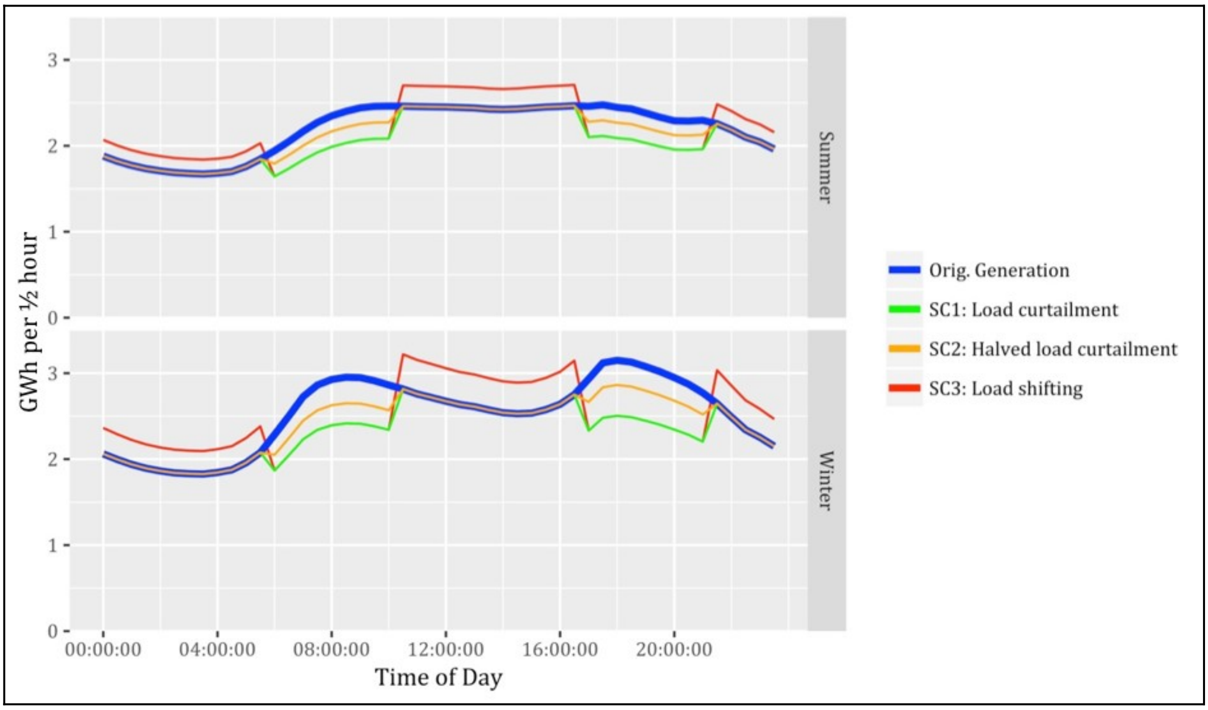

Fig. 26| Estimated daily effects of DR scenarios 1-3 on total electricity generation profile

5.2 Economic potential of DR scenarios

In this paper we estimate the economic value of each DR scenario based on currently available data on spot market prices and CPD charges. First we report estimates of economic value based on spot market prices.

5.2.1 Spot market prices

In a first step, we will analyse the cost of the economic value of DR scenarios. In a second step, savings are presented, and the economic potential of load shifting is elucidated in detail.

We calculated a baseline value for each appliance aggregation. This baseline value consists of the total cost for supplying electricity to consumers.

After adjusting the energy consumption based on the DR scenarios, we apply average spot market prices (no regional consideration) to determine the change in total price over the year from the baseline. Under scenario **one**, the energy consumption is set to zero during peak time periods and reduces the cost to zero during these periods. Halving the load at peaks under scenario **two** halves the baseline cost at peaks. Load shifting under scenario **three** assumes no cost at peaks but considers the increased energy consumption in the prior time interval and, therefore, increased cost during off-peaks.

Based on spot market prices alone, in the baseline scenario, heat pumps have the lowest cost per year at $53M. Hot water heaters, in contrast, cost $240M per year. Refrigerators are in between and cost $136M per year. Aggregating all appliances together generates costs of $430M. In general, the more energy consumption during times of peak, particularly in winter, the higher the cost.

Load curtailment to zero under scenario **one** saves 41% of the cost described in the baseline scenario of refrigerators, and up to 62% of the cost described in the baseline scenario of heat pumps per year. The aggregation of all three appliances generates savings of fifty-two per cent, equivalent to $227M per year. Halving load at peaks decreases the savings by 50% compared to a full load curtailment. This underlines the impact peaks have on the total cost per year. In the load shifting scenario (scenario three), although the total energy consumption stays the same, the timing of demand is adjusted. This scenario achieves 6 to 8% savings compared to the baseline. The aggregation of all three appliances saves 7% of the baseline cost, equivalent to $30M per year. The Economic output 1 (p. 86) depicts the aforementioned cost and savings in more detail.

In the following, we present the results for load shifting (scenario **three**) aggregating heat pumps, hot water heaters, and refrigerators.

Fig. 27 depicts costs for an average day per season in the baseline scenario for each half hour time interval when spot market prices are applied to the aggregated energy consumption profile of heat pumps, hot water heaters, and refrigerators. The figure displays the alternation of average daily spot market prices for each season. We identify the highest costs in winter with up to $120,000 per half-hour in the morning peak, and up to $70,000 in the evening peak. The lowest spot market prices are found in summer with values up to $28,000 per half-hour in the morning peak, and $25,000 in the summer evening peak.

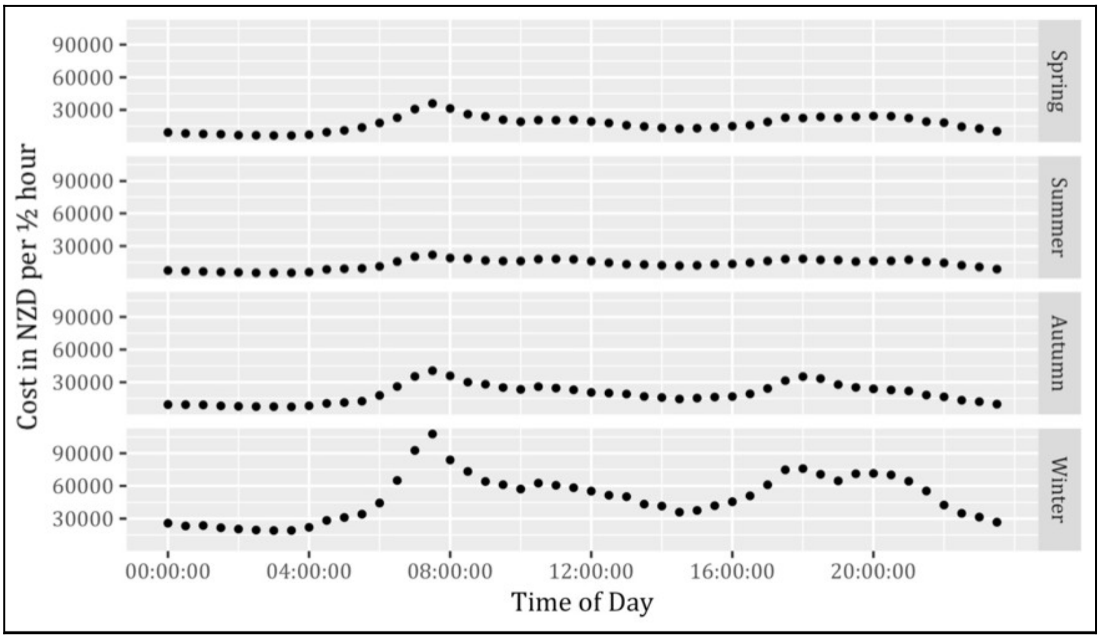

Fig. 27| Estimated daily total spot market prices of baseline scenario (no DR applied)

5.2.2 Incorporating spot market prices and CPD charges

This section focuses particularly on the aggregation of heat pumps, hot water heaters, and refrigerators. In addition to the scenarios described in the section **4.3**, a fourth scenario: response to all CPD events, has been added. This scenario assumes that participants drop all of their load in response to CPD events on a half hour basis (*i.e.* although the CPD event might be only 20 minutes long, load is curtailed for the full half hour) and need to increase energy consumption after the CPD event to retrieve the same level of service. For simplicity we assume that participants that respond to all CPD events only pay spot market prices equivalent to the baseline cost of spot market prices although the price in the half-hour of increased energy consumption might be different.

Fig. 28 shows the total cost per year in million $ when spot market prices as well as CPD charges are considered.

Incorporating CPD charges increases the total cost per year by 25% to $540M in the baseline scenario. This assumes that no DR scenario is applied. Fig. 29 provides the percentage of the baseline cost due to each appliance.

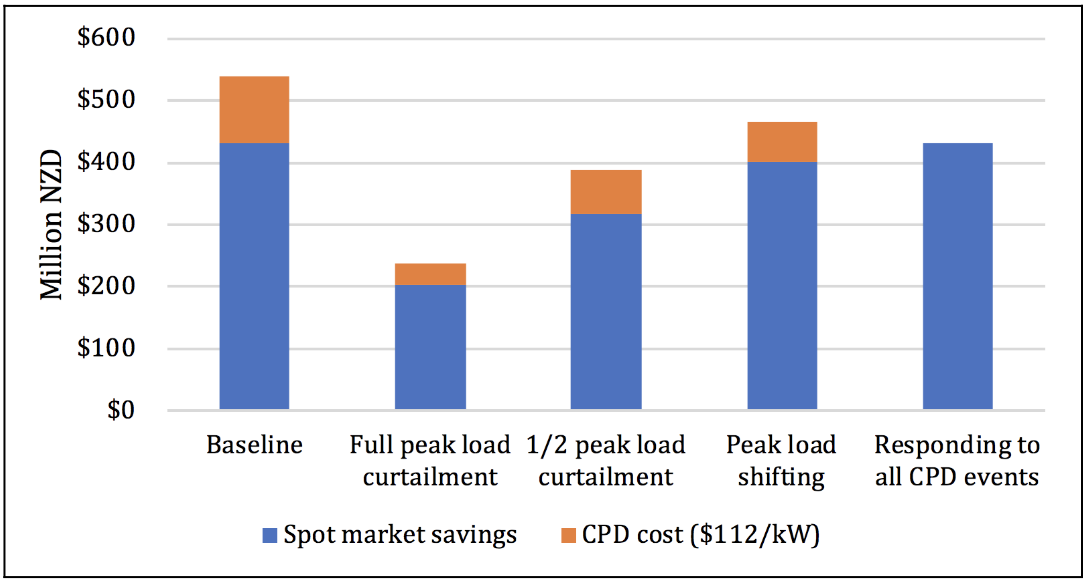

Fig. 28| Cost per year for HP, HW, and REF (scenarios 1-4)

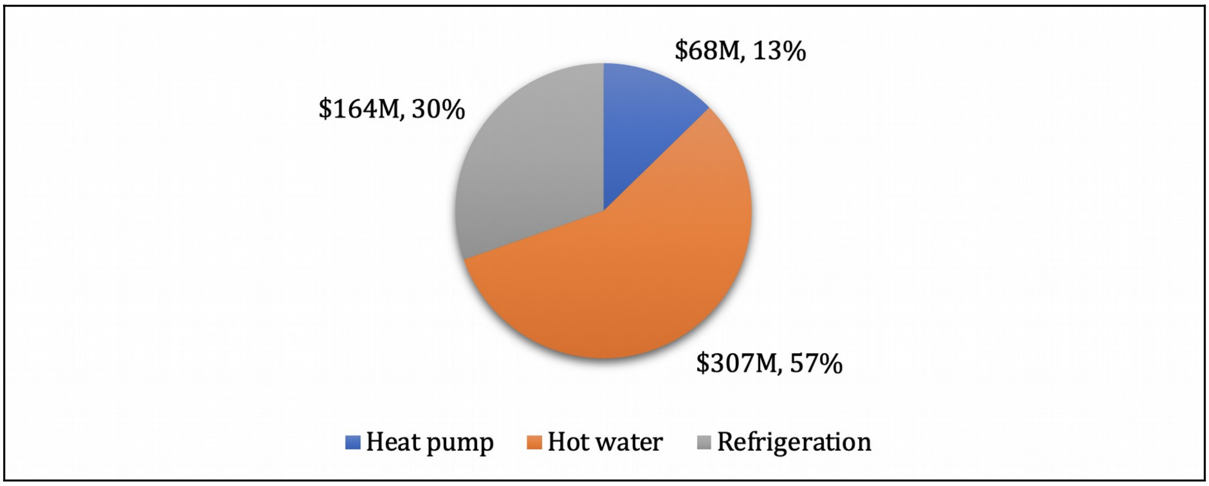

Fig. 29| Baseline costs by appliance per year for HP, HW, and REF in million $

Fifty-seven percent of the total annual costs are due to hot water heaters, followed by refrigerators at thirty percent, and heat pumps with thirteen percent.

The annual costs of each scenario are presented in **Fig. 28**.

Savings relative to the baseline decrease gradually in the DR scenarios one to three. The higher the energy consumption, especially during periods of peak demand, the higher the annual costs. Fig. 30 shows the savings relative to the baseline for all scenarios including DR scenario four: responding to all CPD events.

CPD demand denotes the average load for one year at CPD events in kW per household. This demand constitutes the basis for CPD charges. The higher the CPD demand at CPD events the higher the cost. Load curtailment under scenario **one** decreases the aggregated CPD demand of heat pumps, hot water heaters, and refrigerators per household from 0.85 kW to 0.26 kW. Not all CPD events occur during the defined peak periods, therefore some residual costs CPD costs remain in this scenario.

Halving the energy consumption at times of peaks under scenario **two** reduces CPD savings compared to the baseline scenario by 50%. CPD demand (in kW) increases from

0.26 kW at full load curtailment to 0.55 kW due to the increased energy consumption at times of peaks that coincides with CPD events. Halving energy consumption at peaks generates annual savings of $150M.

Load shifting under scenario **three** is the least beneficial DR scenario in the presented environment but considers all of the energy incorporated in the originally aggregated energy consumption profile. Spot market price savings are reduced to $30M per year and CPD savings take on a value of $42M. Spot market prices and CPD charges at peaks time intervals are zero and shifted to off-peak time intervals one and two. This increase of energy consumption at off-peaks reduces the savings. This scenario generates annual savings relative to the base scenario of $23M per year and a large percentage of this is from avoiding CPD charges.

Responding to all CPD events (scenario **four**) generates savings of $107M per year. From an individual household perspective the peak load shifting scenario equates $78 per year and the reduce congestion scenario to a saving of $95 per year. It is worth remembering that in this scenario DR only occurs for around 100 hours per year compared to 8 hours a day in the other scenarios. Fig. 31 depicts savings by appliance per year for scenario **three** and scenario **four** and clarifies the impact of reducing CPD charges on annual savings.

Analysis of the “responding to all CPD events” scenario showed average national power demand that could be reduced during congestion periods was 650 MW for hot water cylinders, 378 MW for heat pumps, and 233 MW for refrigerators, providing a total of 1,261 MW (or 0.85 kW per household). Economic output 2 (p. 87), Economic output 3 (p. 88), Economic output 4 (p. 89), and Economic output 5 (p. 90) present further results for the four scenarios for costs and savings as totals and per household basis.

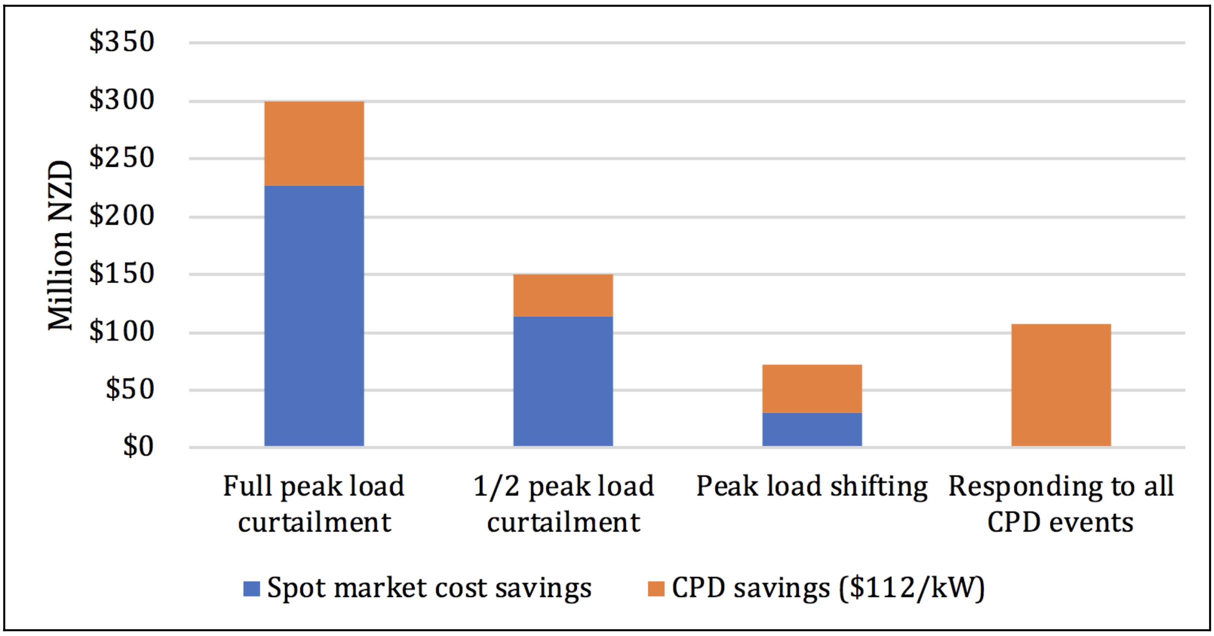

Fig. 30| Savings per year for HP, HW, and REF (scenarios 1-4)

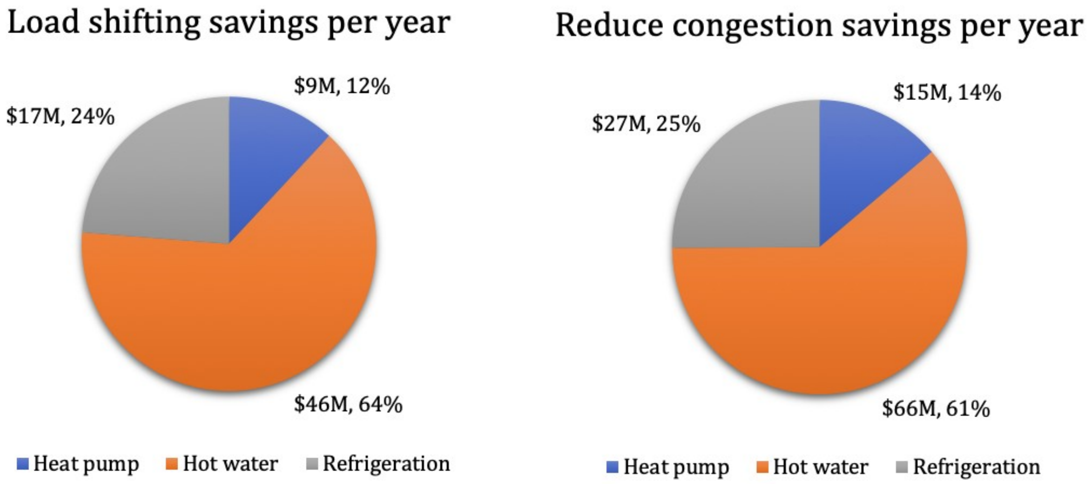

Fig. 31| Left: Peak load shifting savings by appliance per year for HP, HW, and REF. Right: Responding to all CPD events savings by appliance per year for HP, HW, and REF.

6 Summary, recommendations and future work

Our analysis shows that thermo-electric residential appliances, including hot water heaters, heat pumps, and refrigerators represent a significant amount of energy consumption during network peaks. In particular, hot water heaters, refrigerators, and heat pumps accounted for an **estimated** 3,160 MWh, 1,080 MWh, and 879 MWh for an average day of the winter morning peak from 06:00 to 10:00. The evening peak in winter is 2,699 MWh for hot water heaters, 1,080 MWh for refrigerators, and 1,143 MWh for heat pumps for an average day, respectively.

Three DR scenarios consisting of: full load curtailment, halved load curtailment, load shifting during peak-time periods were considered. These scenarios show that DR can reduce load during the winter morning peak period by 20% and by 18% in the evening. This represents an average energy consumption of 5,100 MWh in the winter morning peak per day, equivalent to running Huntly Power Station, the largest thermal power station in New Zealand, with an installed capacity of 953 MW, for 5.5 hours at maximum capacity. In the evening peak this load reduction constitutes 4,920 MWh per day. On a per household level this equates to 3.34 kWh in the winter morning peak and 3.26 kWh in evening peak.

In the summer, less utilisation of heat pumps at peak demand in the morning decreases this proportion to 15% and 14% in the evening. In combination, the appliances modelled could provide a maximum aggregated demand response of 1,600 MW in the winter morning peak, and 1,200 MW in the evening peak. In contrast, Transpower's DR programme for 2013 only made available 134 MW in total from all sources, or just 8% (11%) of the technical potential we have estimated in the winter morning (evening) peak. Further, even Transpower's proposed 635 MW from both industrial and residential DR (Transpower New Zealand Limited, 2014) would still only offer c. 40% of the technical potential we have estimated. However, the DR scenarios in our analysis conduct load curtailment and load shifting on a scale that might be impractical for appliances like heat pumps. As mentioned before, this report does not aim to estimate the realisable potential of DR but provides an overview of maximum DR potential in New Zealand and thus includes DR scenarios that estimate this maximum potential.

An estimate of the value of these DR scenarios was also attempted. For this estimate, current spot market prices were used as a proxy for time-varying prices and CPD charges as a proxy for critical peak charges. These were the only prices considered.

Spot market prices vary over time and season. The highest spot market prices are found in winter and take on values of up to $150 per MWh whereas in summer they remain below $60 per MWh. Spot market prices also vary significantly by region but this was not considered in this analysis.

CPD charges were also considered as part of estimating the economic value of the DR scenarios. CPD charges are based on the demand (in kW) during congestion periods. In the data utilized, CPD events occur only in autumn and winter, often at times of peak demand. The total duration of CPD events is fourteen hours in an average autumn, and eighty-two hours in an average winter.

Applying these charges to the baseline scenario without DR results in a cost of $540M per year in total, with CPD making up 25%. The load shifting scenario results in a saving of $30M in spot market prices and $42M in CPD charges relative to the baseline. This is equivalent to a total cost reduction of 13% per year. An additional scenario consisting of all participants curtailing load during all CPD events (approximately 100 hours per year). This resulted in saving all the CPD charges or a saving of $107M per year.

6.1 Limitations

The reported technical potential of DR estimated in this study is based on a number of simplifying assumptions due to currently available data. The most important assumptions made in this work that could directly affect the DR scenarios are:

- GREENGrid data provide reasonably representative daily profiles for energy use by heat pumps and hot water cylinders in New Zealand households.

- The BRANZ HEEP study's information on appliances reflect current energy consumption patterns in New Zealand (e.g. that the figure of 88% hot water heaters utilising electricity in New Zealand reported in 2007 based on 1996 Census data is still up to date).

- EECA's Energy End Use data for heat pump, hot water demand and refrigeration is accurate and also there is no significant temporal variation in energy demand for refrigeration;

- There is no significant variation in regional residential demand throughout New Zealand.

These assumptions limit the accuracy of the results. Improved data sources that can provide robust energy demand statistics for a nationally and regionally representative sample of New Zealand households would significantly improve the accuracy of these estimates.

The DR scenarios considered were designed to illustrate order of magnitude effects and, are of course, quite simplistic. Real DR strategies are likely to be much more sophisticated, including, for example, methods to smooth the rebound effect and to also be regionally specific. In addition, these results represent the technical potential and do not consider the market systems and consumer behavioural change necessary to actually achieve residential DR in practice. These aspects are likely to reduce the achievable DR.

The method of estimating the economic value of the DR scenarios is also quite simplistic. It used current market prices as a proxy for time-varying prices and uses (one regions) CPD charges as a proxy for national critical peak charges. These estimates therefore only provide a guideline for the value of residential demand response.

6.2 Future work

The results presented here are based on the electricity demand patterns of a small sample of New Zealand households. Future work should ensure a New Zealand representative sample of households and it should also ensure accurate and current statistics on the prevalence of relevant appliances.

Ignoring regional effects in both demand profiles and electricity prices was a significant simplification in the analysis. Further work should definitely include and analyse regional variation as this could prove quite significant. For example, spot market prices have a significant variation by region. Hot water cylinder penetration is also expected to have a lot of variation between the North island, which has reticulated natural gas, and the South Island, as is Heat Pump penetration and usage patterns due to different climatic conditions in each region.

The study focused on hot water cylinders, heat pumps and refrigeration appliances based on EECA's overview of delivered electricity and available monitored appliance data (Anderson et al., 2018; Energy Efficiency and Conservation Authority, 2017). Further analysis could also consider appliances that have the potential to significantly effect residential demand profiles or could have significant potential to be used for DR such as resistive electrical heating. Further key technologies include solar PV, standalone batteries and grid-connected electric vehicles.

Further analyses should also consider the technologies required to actually implement DR at the residential scale. Furthermore, future work should assess whether this type of DR would lead to substantial impact on service provided by appliances (e.g. cooling down of refrigerators during the four-hour load curtailment). Progress in technology and especially in information and communication infrastructure will lead to a wider distribution of smart appliances such as described in the German electricity generator RWE's Smart-Home business model (Rheinisch-Westfälisches Elektrizitätswerk AG, 2015). Appliances in residential households and businesses will become accessible via a wireless-connection and can be connected to automated mechanisms that consider both customer preference and DR signals from system operators. Furthermore, Fast Instantaneous Reserve and Sustained Instantaneous Reserve describe technologies that could be utilised for DR and should be considered in further analysis and be connected to CPD modelling. This report focused on savings instead of revenues for participating in Fast

Instantaneous and Sustained Instantaneous Reserve programmes. such as described in Transpower's DR programme of section 3.5.

Market structures and mechanisms do not currently exist to realise the potential for residential DR. Our approach to estimating economic value provides some rudimentary examples of the market structures that might be required. Further work is needed to explore more optimal market mechanisms to engage residential consumers in DR.

Finally, and perhaps most importantly, this study has not included any consideration of the behavioural change necessary to realise this DR potential. Furthermore, this study does not determine a control strategy that would, if incorporated, have the smallest impact on energy usage pattern and services. Changing energy behaviours is difficult (Srivastava, Van Passel, & Laes, 2018; Wang, Zhang, Yin, & Zhang, 2011) and the presented DR scenarios, if implemented, would have impact on the life quality of customers. A thorough analysis considering social habits and attitudes towards DR and its influence (Fell, Shipworth, Huebner, & Elwell, 2015; Spence, Demski, Butler, Parkhill, & Pidgeon, 2015) is thus necessary to understand how much of the technical potential would actually be realisable in New Zealand. This analysis should incorporate customers as well as key participants in the electricity value chain to illuminate DR opportunities and challenges at the different levels of the electricity system and elaborate the attractiveness of DR scenarios for residential customers in New Zealand based on the analysis of social habits.

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Appendix 1: Assumptions

Assumption 1: Pertaining DR scenarios and energy potential

1. GREENGrid data is sufficiently representative of New Zealand households.
2. BRANZ information of appliances are correct and can be used to display current energy consumption patterns in New Zealand (e.g. the 1996 figure of 88% hot water heaters utilising electricity in New Zealand is still up to date).
3. BRANZ values for total energy consumption of appliances are preferred to those from EECA. This prevents overestimation of results.
4. Census 2013 is a sufficient representation of current New Zealand households.
5. Incorporation of two different sources of information on the total number of households in New Zealand is unproblematic. (BRANZ reports distinguish number of households in reports of hot water heaters and heat pumps. See section 4.2)
6. Determination of peak time intervals based on electricity generation is accurate.
7. Seasonal load average (1min granularity) of GREENGrid dataset represents the correct proportion of load for all households in New Zealand when converted to half hour proportion and scaled to BRANZ/EECA total energy consumption in GWh.
8. Load shifting to a time prior to peak demand is feasible and equivalent of pre-heating (hot water heaters, heat pumps) and pre-cooling (refrigerators).
9. Estimates on electricity generation can be drawn from one month of data in the middle of the season (trading granularity only available for up to one month).
10. Absence of measured appliance data (refrigerators) is replaced with a flat energy consumption profile representing in sum the total energy consumption for the individual appliance based on EECA data for 2015.
11. SC1 load curtailment: Curtailed energy consumption can be reduced without any effects on the consumption in other times.
12. SC2 ½ load curtailment: Energy consumption at peaks can be halved without having effects on other times.
13. SC3 load shifting: Energy consumption at peaks can be shifted in the prior time interval.
14. Scenarios are used to assess the technical potential of DR. The realisable potential will differ from the scenario output.

Assumption 2: Pertaining economic potential of DR scenarios

1. Seasonal average of spot market prices for each region represents reality.
2. Spot market prices and CPD charges do not change when load is curtailed or shifted.
3. The electricity price only exists out of two components, spot market prices and CPD charge.
4. Using CPD charge information from Aurora Energy represent New Zealand accurate information on CPD charges.
5. Applying commercial CPD charges on household appliance profiles represent real cost that lines companies face.
6. CPD charge scenarios one to three incorporate all assumptions from the aforementioned demand response scenarios.
7. In CPD charge scenario four households respond to each CPD event.
8. There are no CPD events (hours) in spring and summer.
9. Spot market prices do not change between CPD event and increased energy consumption in CPD scenario four

Appendix 2: Energy potential tables

Energy output 1: HP SC1 total New Zealand per day in MWh

Season	Time-period	Potential curtailment
Spring	Evening Peak	453.20
Spring	Morning Peak	401.21
Spring	Off Peak 1	319.79
Spring	Off Peak 2	284.61
Summer	Evening Peak	308.93
Summer	Morning Peak	120.06
Summer	Off Peak 1	251.19
Summer	Off Peak 2	290.89
Autumn	Evening Peak	447.02
Autumn	Morning Peak	333.43
Autumn	Off Peak 1	329.06
Autumn	Off Peak 2	264.57
Winter	Evening Peak	1143.41
Winter	Morning Peak	879.38
Winter	Off Peak 1	716.47
Winter	Off Peak 2	553.04

Energy output 2: HP SC1 total New Zealand per season in GWh

Season	Time-period	Potential curtailment
Spring	Evening Peak	40.79
Spring	Morning Peak	36.11
Spring	Off Peak 1	28.78
Spring	Off Peak 2	25.61
Summer	Evening Peak	27.80
Summer	Morning Peak	10.81
Summer	Off Peak 1	22.61
Summer	Off Peak 2	26.18
Autumn	Evening Peak	40.23
Autumn	Morning Peak	30.01
Autumn	Off Peak 1	29.62
Autumn	Off Peak 2	23.81
Winter	Evening Peak	102.91
Winter	Morning Peak	79.14
Winter	Off Peak 1	64.48
Winter	Off Peak 2	49.77

Energy output 3: HP SC2 total New Zealand per day in MWh

Season	Time-period	Potential curtailment
Spring	Evening Peak	226.60
Spring	Morning Peak	200.61
Spring	Off Peak 1	319.79
Spring	Off Peak 2	284.61
Summer	Evening Peak	154.46
Summer	Morning Peak	60.03
Summer	Off Peak 1	251.19
Summer	Off Peak 2	290.89
Autumn	Evening Peak	223.51

Autumn	Morning Peak	166.72
Autumn	Off Peak 1	329.06
Autumn	Off Peak 2	264.57
Winter	Evening Peak	571.70
Winter	Morning Peak	439.69
Winter	Off Peak 1	716.47
Winter	Off Peak 2	553.04

Energy output 4: HP SC2 total New Zealand per season in GWh

Season	Time-period	Potential curtailment
Spring	Evening Peak	20.39
Spring	Morning Peak	18.05
Spring	Off Peak 1	28.78
Spring	Off Peak 2	25.61
Summer	Evening Peak	13.90
Summer	Morning Peak	5.40
Summer	Off Peak 1	22.61
Summer	Off Peak 2	26.18
Autumn	Evening Peak	20.12
Autumn	Morning Peak	15.00
Autumn	Off Peak 1	29.62
Autumn	Off Peak 2	23.81
Winter	Evening Peak	51.45
Winter	Morning Peak	39.57
Winter	Off Peak 1	64.48
Winter	Off Peak 2	49.77

Energy output 5: HW SC1 total New Zealand per day in MWh

Season	Time-period	Potential curtailment
Spring	Evening Peak	2480.78
Spring	Morning Peak	2905.24
Spring	Off Peak 1	1901.66
Spring	Off Peak 2	2316.55
Summer	Evening Peak	1732.34
Summer	Morning Peak	1950.78
Summer	Off Peak 1	1580.35
Summer	Off Peak 2	1796.21
Autumn	Evening Peak	2361.47
Autumn	Morning Peak	2857.11
Autumn	Off Peak 1	1719.27
Autumn	Off Peak 2	2423.75
Winter	Evening Peak	2699.70
Winter	Morning Peak	3160.19
Winter	Off Peak 1	2039.42
Winter	Off Peak 2	2895.05

Energy output 6: HW SC1 total New Zealand per season in GWh

Season	Time-period	Potential curtailment
Spring	Evening Peak	223.27
Spring	Morning Peak	261.47
Spring	Off Peak 1	171.15
Spring	Off Peak 2	208.49
Summer	Evening Peak	155.91
Summer	Morning Peak	175.57
Summer	Off Peak 1	142.23
Summer	Off Peak 2	161.66
Autumn	Evening Peak	212.53
Autumn	Morning Peak	257.14
Autumn	Off Peak 1	154.73
Autumn	Off Peak 2	218.14
Winter	Evening Peak	242.97
Winter	Morning Peak	284.42
Winter	Off Peak 1	183.55
Winter	Off Peak 2	260.55

Energy output 7: HW SC2 total New Zealand per day in MWh

Season	Time-period	Potential curtailment
Spring	Evening Peak	1240.39
Spring	Morning Peak	1452.62
Spring	Off Peak 1	1901.66
Spring	Off Peak 2	2316.55
Summer	Evening Peak	866.17
Summer	Morning Peak	975.39
Summer	Off Peak 1	1580.35
Summer	Off Peak 2	1796.21
Autumn	Evening Peak	1180.73
Autumn	Morning Peak	1428.55
Autumn	Off Peak 1	1719.27
Autumn	Off Peak 2	2423.75
Winter	Evening Peak	1349.85
Winter	Morning Peak	1580.09
Winter	Off Peak 1	2039.41
Winter	Off Peak 2	2895.05

Energy output 8: HW SC2 total New Zealand per season in GWh

Season	Time-period	Potential curtailment
Spring	Evening Peak	111.64
Spring	Morning Peak	130.74
Spring	Off Peak 1	171.15
Spring	Off Peak 2	208.49
Summer	Evening Peak	77.96
Summer	Morning Peak	87.78
Summer	Off Peak 1	142.23
Summer	Off Peak 2	161.66
Autumn	Evening Peak	106.27
Autumn	Morning Peak	128.57
Autumn	Off Peak 1	154.73

Autumn	Off Peak 2	218.14
Winter	Evening Peak	121.49
Winter	Morning Peak	142.21
Winter	Off Peak 1	183.55
Winter	Off Peak 2	260.55

Energy output 9: REF SC1 total New Zealand per day in MWh

Season	Time-period	Potential curtailment
Spring	Evening Peak	1080.21
Spring	Morning Peak	1080.21
Spring	Off Peak 1	2040.39
Spring	Off Peak 2	1560.30
Summer	Evening Peak	1080.21
Summer	Morning Peak	1080.21
Summer	Off Peak 1	2040.39
Summer	Off Peak 2	1560.30
Autumn	Evening Peak	1080.21
Autumn	Morning Peak	1080.21
Autumn	Off Peak 1	2040.39
Autumn	Off Peak 2	1560.30
Winter	Evening Peak	1080.21
Winter	Morning Peak	1080.21
Winter	Off Peak 1	2040.39
Winter	Off Peak 2	1560.30

Energy output 10: REF SC1 total New Zealand per season in GWh

Season	Time-period	Potential curtailment
Spring	Evening Peak	97.22
Spring	Morning Peak	97.22
Spring	Off Peak 1	183.64
Spring	Off Peak 2	140.43
Summer	Evening Peak	97.22
Summer	Morning Peak	97.22
Summer	Off Peak 1	183.64
Summer	Off Peak 2	140.43
Autumn	Evening Peak	97.22
Autumn	Morning Peak	97.22
Autumn	Off Peak 1	183.64
Autumn	Off Peak 2	140.43
Winter	Evening Peak	97.22
Winter	Morning Peak	97.22
Winter	Off Peak 1	183.64
Winter	Off Peak 2	140.43

Energy output 11: REF SC2 total New Zealand per day in MWh

Season	Time-period	Potential curtailment
Spring	Evening Peak	540.10
Spring	Morning Peak	540.10
Spring	Off Peak 1	2040.39
Spring	Off Peak 2	1560.30
Summer	Evening Peak	540.10
Summer	Morning Peak	540.10
Summer	Off Peak 1	2040.39
Summer	Off Peak 2	1560.30
Autumn	Evening Peak	540.10
Autumn	Morning Peak	540.10
Autumn	Off Peak 1	2040.39
Autumn	Off Peak 2	1560.30
Winter	Evening Peak	540.10
Winter	Morning Peak	540.10
Winter	Off Peak 1	2040.39
Winter	Off Peak 2	1560.30

Energy output 12: REF SC2 total New Zealand per season in GWh

Season	Time-period	Potential curtailment
Spring	Evening Peak	48.61
Spring	Morning Peak	48.61
Spring	Off Peak 1	183.64
Spring	Off Peak 2	140.43
Summer	Evening Peak	48.61
Summer	Morning Peak	48.61
Summer	Off Peak 1	183.64
Summer	Off Peak 2	140.43
Autumn	Evening Peak	48.61
Autumn	Morning Peak	48.61
Autumn	Off Peak 1	183.64
Autumn	Off Peak 2	140.43
Winter	Evening Peak	48.61
Winter	Morning Peak	48.61
Winter	Off Peak 1	183.64
Winter	Off Peak 2	140.43

Energy output 13: HP&HW SC1 total New Zealand per day in MWh

Season	Time-period	Potential curtailment
Spring	Evening Peak	2933.98
Spring	Morning Peak	3306.45
Spring	Off Peak 1	2221.45
Spring	Off Peak 2	2601.16
Summer	Evening Peak	2041.27
Summer	Morning Peak	2070.84

Summer	Off Peak 1	1831.54
Summer	Off Peak 2	2087.10
Autumn	Evening Peak	2808.49
Autumn	Morning Peak	3190.54
Autumn	Off Peak 1	2048.33
Autumn	Off Peak 2	2688.32
Winter	Evening Peak	3843.11
Winter	Morning Peak	4039.57
Winter	Off Peak 1	2755.88
Winter	Off Peak 2	3448.09

Energy output 14: HP&HW SC1 total New Zealand per season in GWh

Season	Time-period	Potential curtailment
Spring	Evening Peak	264.06
Spring	Morning Peak	297.58
Spring	Off Peak 1	199.93
Spring	Off Peak 2	234.10
Summer	Evening Peak	183.71
Summer	Morning Peak	186.38
Summer	Off Peak 1	164.84
Summer	Off Peak 2	187.84
Autumn	Evening Peak	252.76
Autumn	Morning Peak	287.15
Autumn	Off Peak 1	184.35
Autumn	Off Peak 2	241.95
Winter	Evening Peak	345.88
Winter	Morning Peak	363.56
Winter	Off Peak 1	248.03
Winter	Off Peak 2	310.33

Energy output 15: HP&HW SC2 total New Zealand per day in MWh

Season	Time-period	Potential curtailment
Spring	Evening Peak	1466.99
Spring	Morning Peak	1653.23
Spring	Off Peak 1	4822.61
Spring	Off Peak 2	1020.63
Summer	Evening Peak	1035.42
Summer	Morning Peak	3918.64
Summer	Off Peak 1	1404.24
Summer	Off Peak 2	1595.27
Autumn	Evening Peak	4736.65
Autumn	Morning Peak	1921.56
Autumn	Off Peak 1	2019.78
Autumn	Off Peak 2	6203.97
Winter	Evening Peak	1466.99
Winter	Morning Peak	1653.23
Winter	Off Peak 1	4822.61
Winter	Off Peak 2	1020.63

Energy output 16: HP&HW SC2 total New Zealand per season in GWh

Season	Time-period	Potential curtailment
Spring	Evening Peak	132.03
Spring	Morning Peak	148.79
Spring	Off Peak 1	434.03
Spring	Off Peak 2	91.86
Summer	Evening Peak	93.19
Summer	Morning Peak	352.68
Summer	Off Peak 1	126.38
Summer	Off Peak 2	143.57
Autumn	Evening Peak	426.30
Autumn	Morning Peak	172.94
Autumn	Off Peak 1	181.78
Autumn	Off Peak 2	558.36
Winter	Evening Peak	132.03
Winter	Morning Peak	148.79
Winter	Off Peak 1	434.03
Winter	Off Peak 2	91.86

Energy output 17: HP, HW&REF SC1 total New Zealand per day in MWh

Season	Time-period	Potential curtailment
Spring	Evening Peak	4014.19
Spring	Morning Peak	4386.66
Spring	Off Peak 1	4261.85
Spring	Off Peak 2	4161.46
Summer	Evening Peak	3121.47
Summer	Morning Peak	3151.05
Summer	Off Peak 1	3871.93
Summer	Off Peak 2	3647.40
Autumn	Evening Peak	3888.69
Autumn	Morning Peak	4270.75
Autumn	Off Peak 1	4088.72
Autumn	Off Peak 2	4248.62
Winter	Evening Peak	4923.32
Winter	Morning Peak	5119.78
Winter	Off Peak 1	4796.27
Winter	Off Peak 2	5008.39

Energy output 18: HP, HW&REF SC1 total New Zealand per season in GWh

Season	Time-period	Potential curtailment
Spring	Evening Peak	361.28
Spring	Morning Peak	394.80
Spring	Off Peak 1	383.57
Spring	Off Peak 2	374.53
Summer	Evening Peak	280.93
Summer	Morning Peak	283.59
Summer	Off Peak 1	348.47
Summer	Off Peak 2	328.27

Autumn	Evening Peak	349.98
Autumn	Morning Peak	384.37
Autumn	Off Peak 1	367.99
Autumn	Off Peak 2	382.38
Winter	Evening Peak	443.10
Winter	Morning Peak	460.78
Winter	Off Peak 1	431.66
Winter	Off Peak 2	450.76

Energy output 19: HP, HW&REF SC2 total New Zealand per day in MWh

Season	Time-period	Potential curtailment
Spring	Evening Peak	2007.09
Spring	Morning Peak	2193.33
Spring	Off Peak 1	4261.85
Spring	Off Peak 2	4161.46
Summer	Evening Peak	1560.74
Summer	Morning Peak	1575.52
Summer	Off Peak 1	3871.93
Summer	Off Peak 2	3647.40
Autumn	Evening Peak	1944.35
Autumn	Morning Peak	2135.38
Autumn	Off Peak 1	4088.72
Autumn	Off Peak 2	4248.62
Winter	Evening Peak	2461.66
Winter	Morning Peak	2559.89
Winter	Off Peak 1	4796.27
Winter	Off Peak 2	5008.39

Energy output 20: HP, HW&REF SC2 total New Zealand per season in GWh

Season	Time-period	Potential curtailment
Spring	Evening Peak	180.64
Spring	Morning Peak	197.40
Spring	Off Peak 1	383.57
Spring	Off Peak 2	374.53
Summer	Evening Peak	140.47
Summer	Morning Peak	141.80
Summer	Off Peak 1	348.47
Summer	Off Peak 2	328.27
Autumn	Evening Peak	174.99
Autumn	Morning Peak	192.18
Autumn	Off Peak 1	367.99
Autumn	Off Peak 2	382.38
Winter	Evening Peak	221.55
Winter	Morning Peak	230.39
Winter	Off Peak 1	431.66
Winter	Off Peak 2	450.76

Appendix 3: Economic potential tables

Economic output 1: Spot market price calculation

Appliance	*Scenario*	*Cost in million $*	*Savings in million $*	*Savings in %*
HP	Baseline	$ 53.38	-	-
HP	Load curtailment to zero	$ 20.23	$ 33.15	62%
HP	Load curtailment 0.5	$ 36.80	$ 16.57	31%
HP	Load shifting	$ 50.00	$ 3.38	6%
HW	Baseline	$ 240.99	-	-
HW	Load curtailment to zero	$ 103.16	$ 137.83	57%
HW	Load curtailment 0.5	$ 172.07	$ 68.92	29%
HW	Load shifting	$ 221.59	$ 19.40	8%
REF	Baseline	$ 136.56	-	-
REF	Load curtailment to zero	$ 80.35	$ 56.20	41%
REF	Load curtailment 0.5	$ 108.46	$ 28.10	21%
REF	Load shifting	$ 129.47	$ 7.09	5%
HP & HW	Baseline	$ 294.36	-	-
HP & HW	Load curtailment to zero	$ 123.39	$ 170.98	58%
HP & HW	Load curtailment 0.5	$ 208.88	$ 85.49	29%
HP & HW	Load shifting	$ 271.59	$ 22.78	8%
HP & HW & REF	Baseline	$ 430.92	-	-
HP & HW & REF	Load curtailment to zero	$ 203.74	$ 227.18	52%
HP & HW & REF	Load curtailment 0.5	$ 317.33	$ 113.59	26%
HP & HW & REF	Load shifting	$ 401.06	$ 29.87	7%

Economic output 2: CPD charges per year SC1

Appliance	$\acute{D}_{CP}$ *in kW*	*Price scenario in \$/*$\acute{D}_{CP}$ *kW*	*Cost in \$ per household*	*Cost in million \$ total*
HP	0.05	PS1: \$ 112.38	\$ 5.90	\$ 3.04
HP	0.05	PS2: \$ 123.63	\$ 6.49	\$ 3.34
HP	0.05	PS3: \$ 131.98	\$ 6.92	\$ 3.57
HP	0.05	PS4: \$ 171.48	\$ 9.00	\$ 4.63
HW	0.14	PS1: \$ 112.38	\$ 15.93	\$ 21.72
HW	0.14	PS2: \$ 123.63	\$ 17.52	\$ 23.90
HW	0.14	PS3: \$ 131.98	\$ 18.71	\$ 25.51
HW	0.14	PS4: \$ 171.48	\$ 24.30	\$ 33.15
REF	0.06	PS1: \$ 112.38	\$ 6.87	\$ 10.01
REF	0.06	PS2: \$ 123.63	\$ 7.55	\$ 11.01
REF	0.06	PS3: \$ 131.98	\$ 8.06	\$ 11.75
REF	0.06	PS4: \$ 171.48	\$ 10.45	\$ 15.27
HP & HW	0.19	PS1: \$ 112.38	\$ 21.83	\$ 24.76
HP & HW	0.19	PS2: \$ 123.63	\$ 24.01	\$ 27.24
HP & HW	0.19	PS3: \$ 131.98	\$ 25.63	\$ 29.08
HP & HW	0.19	PS4: \$ 171.48	\$ 33.30	\$ 37.78
HP & HW & REF	0.26	PS1: \$ 112.38	\$ 28.69	\$ 34.77
HP & HW & REF	0.26	PS2: \$ 123.63	\$ 31.56	\$ 38.25
HP & HW & REF	0.26	PS3: \$ 131.98	\$ 33.70	\$ 40.83
HP & HW & REF	0.26	PS4: \$ 171.48	\$ 43.78	\$ 53.05

Economic output 3: CPD charges per year SC2

Appliance	$\acute{D}_{CP}$ in kW	Price scenario in \$/$\acute{D}_{CP}$ kW	Cost in \$ per household	Cost in million \$ total
HP	0.15	PS1: \$ 112.38	\$ 17.37	\$ 8.94
HP	0.15	PS2: \$ 123.63	\$ 19.10	\$ 9.84
HP	0.15	PS3: \$ 131.98	\$ 20.40	\$ 10.50
HP	0.15	PS4: \$ 171.48	\$ 26.50	\$ 13.65
HW	0.28	PS1: \$ 112.38	\$ 32.06	\$ 43.73
HW	0.28	PS2: \$ 123.63	\$ 35.27	\$ 48.11
HW	0.28	PS3: \$ 131.98	\$ 37.66	\$ 51.36
HW	0.28	PS4: \$ 171.48	\$ 48.93	\$ 66.73
REF	0.11	PS1: \$ 112.38	\$ 12.69	\$ 18.49
REF	0.11	PS2: \$ 123.63	\$ 13.96	\$ 20.34
REF	0.11	PS3: \$ 131.98	\$ 14.90	\$ 21.72
REF	0.11	PS4: \$ 171.48	\$ 19.36	\$ 28.22
HP & HW	0.44	PS1: \$ 112.38	\$ 49.43	\$ 52.68
HP & HW	0.44	PS2: \$ 123.63	\$ 54.38	\$ 57.95
HP & HW	0.44	PS3: \$ 131.98	\$ 58.05	\$ 61.87
HP & HW	0.44	PS4: \$ 171.48	\$ 75.42	\$ 80.38
HP & HW & REF	0.55	PS1: \$ 112.38	\$ 62.12	\$ 71.17
HP & HW & REF	0.55	PS2: \$ 123.63	\$ 68.33	\$ 78.29
HP & HW & REF	0.55	PS3: \$ 131.98	\$ 72.95	\$ 83.58
HP & HW & REF	0.55	PS4: \$ 171.48	\$ 94.78	\$ 108.59

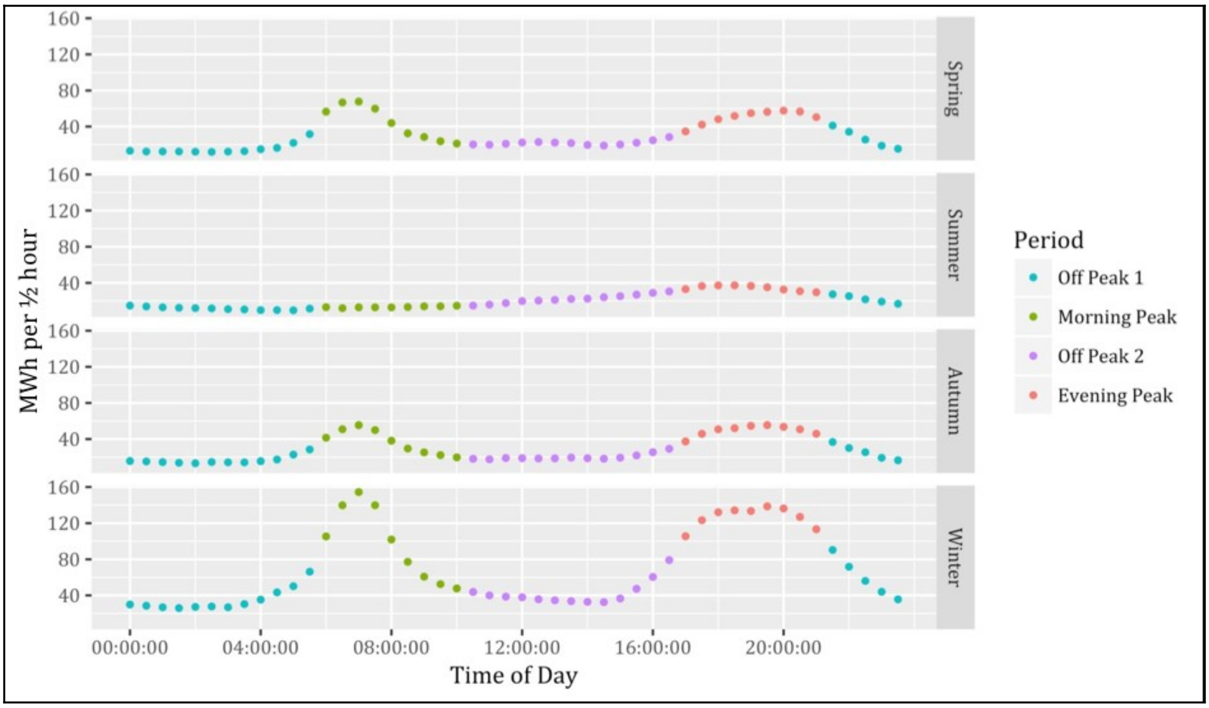
Economic output 4: CPD charges per year SC3

Appliance	$\acute{D}_{CP}$ in kW	Price scenario in $/$\acute{D}_{CP}$ kW	Cost in $ per house-hold	Cost in million $ total
HP	0.17	PS1: $ 112.38	$ 18.70	$ 9.63
HP	0.17	PS2: $ 123.63	$ 20.58	$ 10.60
HP	0.17	PS3: $ 131.98	$ 21.97	$ 11.31
HP	0.17	PS4: $ 171.48	$ 28.54	$ 14.70
HW	0.25	PS1: $ 112.38	$ 28.36	$ 38.68
HW	0.25	PS2: $ 123.63	$ 31.19	$ 42.55
HW	0.25	PS3: $ 131.98	$ 33.30	$ 45.42
HW	0.25	PS4: $ 171.48	$ 43.27	$ 59.01
REF	0.10	PS1: $ 112.38	$ 11.60	$ 16.91
REF	0.10	PS2: $ 123.63	$ 12.76	$ 18.60
REF	0.10	PS3: $ 131.98	$ 13.63	$ 19.86
REF	0.10	PS4: $ 171.48	$ 17.70	$ 25.80
HP & HW	0.43	PS1: $ 112.38	$ 47.06	$ 48.31
HP & HW	0.43	PS2: $ 123.63	$ 51.77	$ 53.14
HP & HW	0.43	PS3: $ 131.98	$ 55.27	$ 56.74
HP & HW	0.43	PS4: $ 171.48	$ 71.81	$ 73.71
HP & HW & REF	0.52	PS1: $ 112.38	$ 58.67	$ 65.22
HP & HW & REF	0.52	PS2: $ 123.63	$ 64.53	$ 71.74
HP & HW & REF	0.52	PS3: $ 131.98	$ 68.90	$ 76.59
HP & HW & REF	0.52	PS4: $ 171.48	$ 89.51	$ 99.51

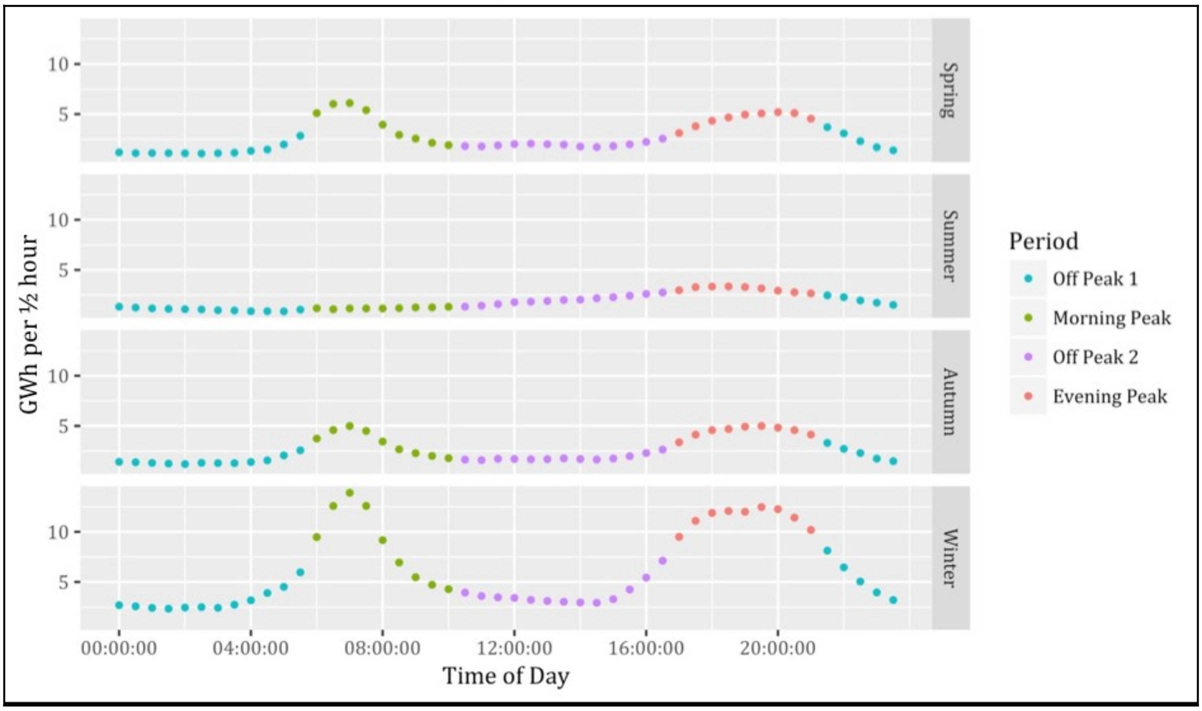
Economic output 5: CPD charges per year SC4 (Load reduction at all CPD events)

Appliance	$\acute{D}_{CP}$ *in kW*	*Price scenario in \$/$\acute{D}_{CP}$ kW*	*Cost in \$ per household*	*Cost in million \$ total*
HP	0.26	PS1: \$ 112.38	\$ 28.84	\$ 14.85
HP	0.26	PS2: \$ 123.63	\$ 31.72	\$ 16.34
HP	0.26	PS3: \$ 131.98	\$ 33.87	\$ 17.44
HP	0.26	PS4: \$ 171.48	\$ 44.00	\$ 22.66
HW	0.42	PS1: \$ 112.38	\$ 48.20	\$ 65.74
HW	0.42	PS2: \$ 123.63	\$ 53.02	\$ 72.31
HW	0.42	PS3: \$ 131.98	\$ 56.61	\$ 77.20
HW	0.42	PS4: \$ 171.48	\$ 73.55	\$ 100.31
REF	0.16	PS1: \$ 112.38	\$ 18.51	\$ 26.98
REF	0.16	PS2: \$ 123.63	\$ 20.36	\$ 29.68
REF	0.16	PS3: \$ 131.98	\$ 21.74	\$ 31.68
REF	0.16	PS4: \$ 171.48	\$ 28.24	\$ 41.16
HP & HW	0.69	PS1: \$ 112.38	\$ 77.04	\$ 80.59
HP & HW	0.69	PS2: \$ 123.63	\$ 84.75	\$ 88.66
HP & HW	0.69	PS3: \$ 131.98	\$ 90.48	\$ 94.65
HP & HW	0.69	PS4: \$ 171.48	\$ 117.55	\$ 122.97
HP & HW & REF	0.85	PS1: \$ 112.38	\$ 95.55	\$ 107.57
HP & HW & REF	0.85	PS2: \$ 123.63	\$ 105.11	\$ 118.33
HP & HW & REF	0.85	PS3: \$ 131.98	\$ 112.21	\$ 126.33
HP & HW & REF	0.85	PS4: \$ 171.48	\$ 145.55	\$ 164.13

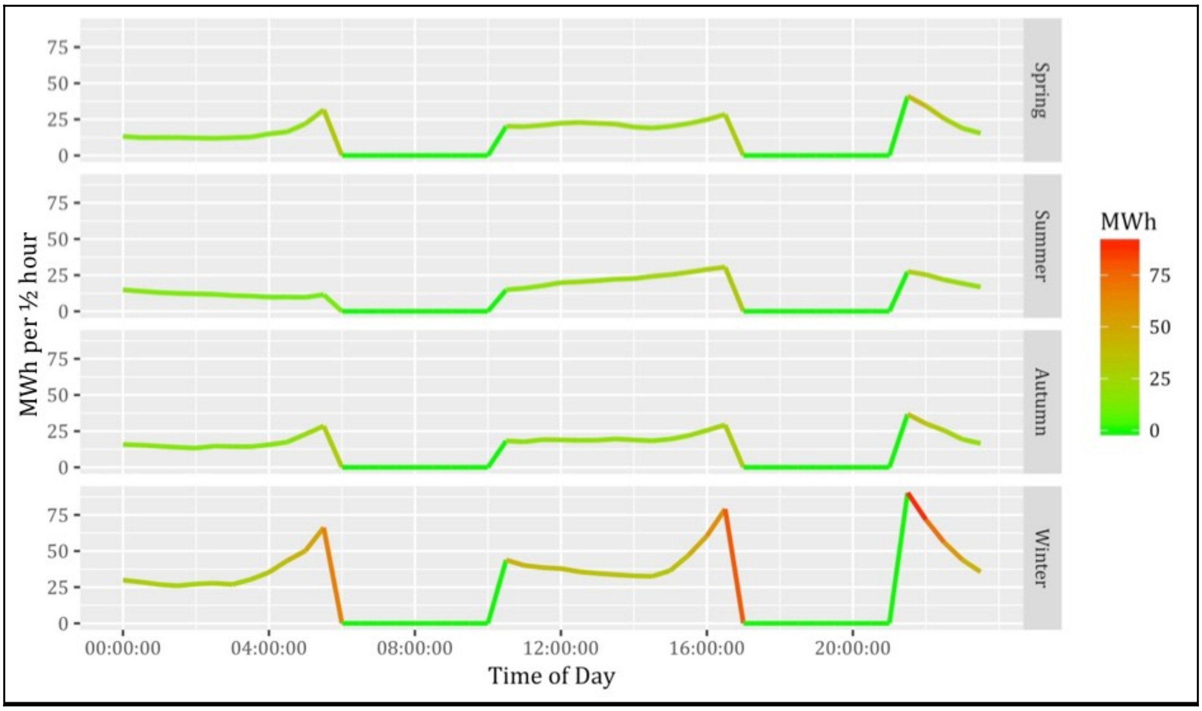
Appendix 4: Further visualisation of DR scenario



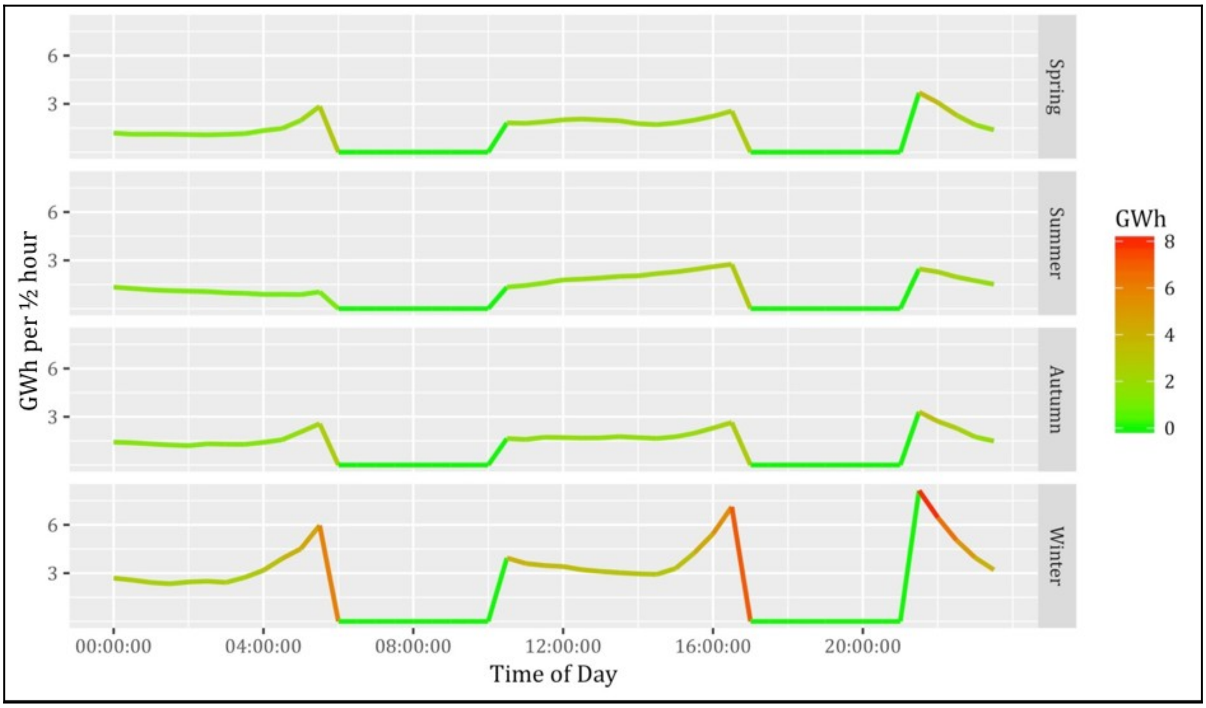
Graphic 1| HP total New Zealand energy consumption per day in MWh



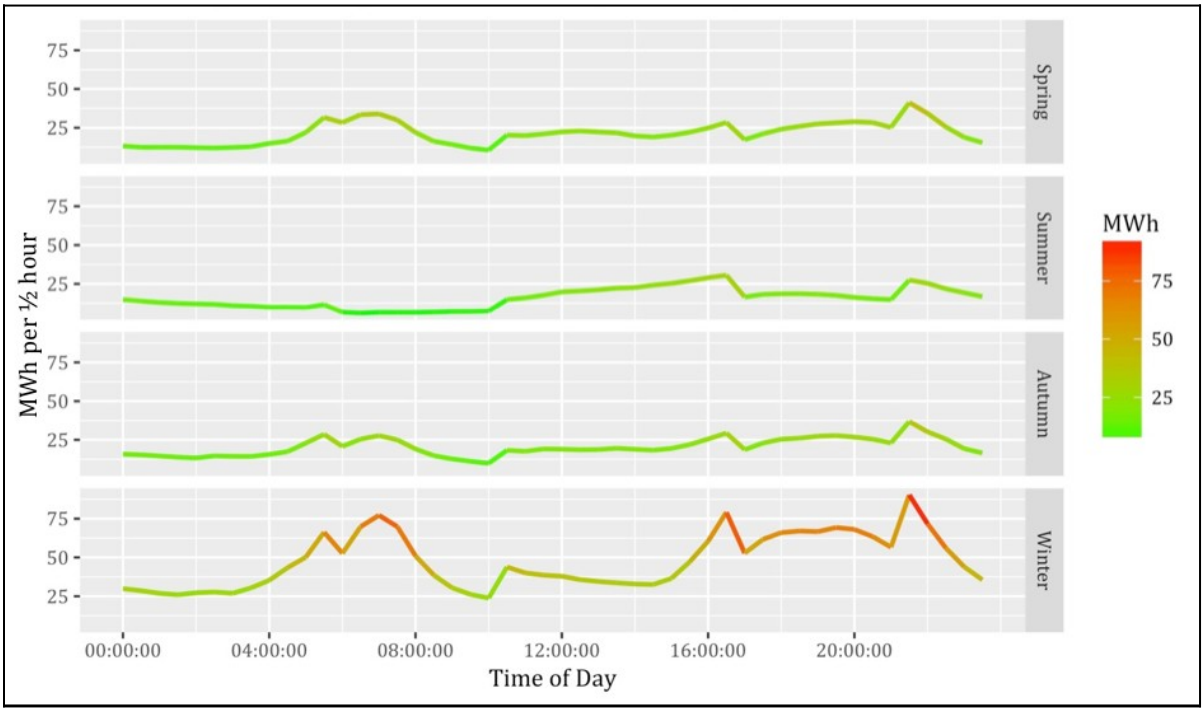
Graphic 2| HP total New Zealand energy consumption per season in GWh



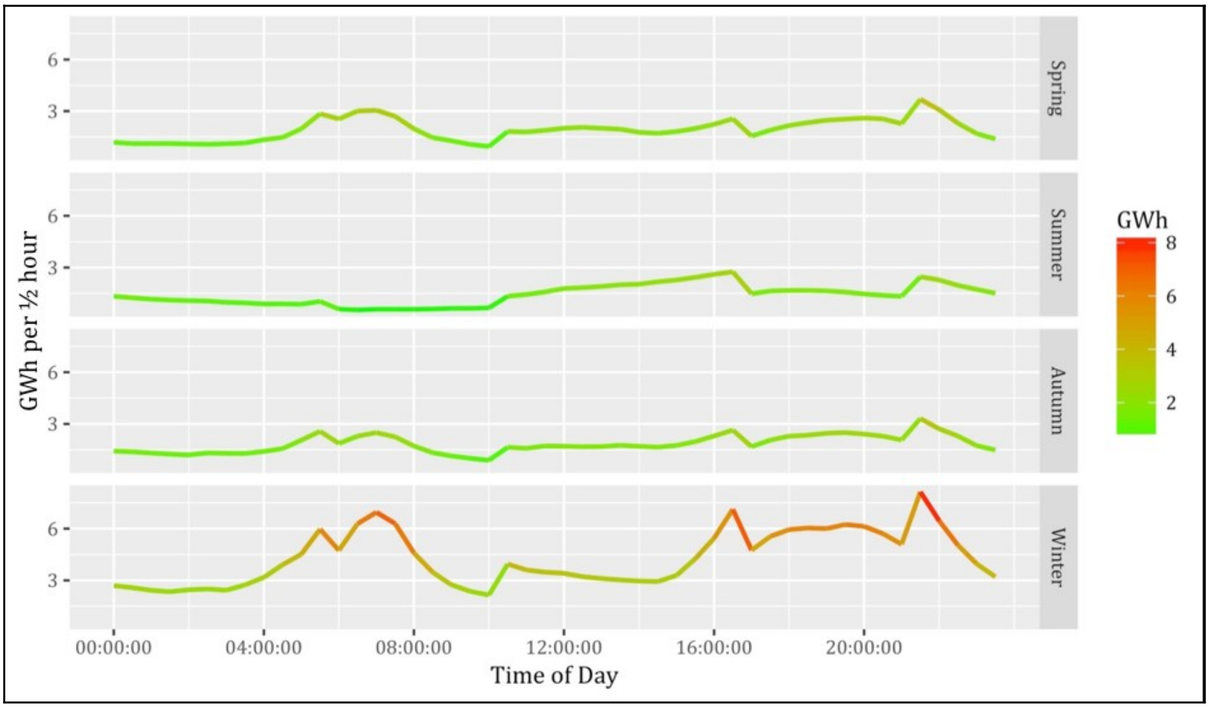
Graphic 3| HP SC1 total New Zealand energy consumption per day in MWh



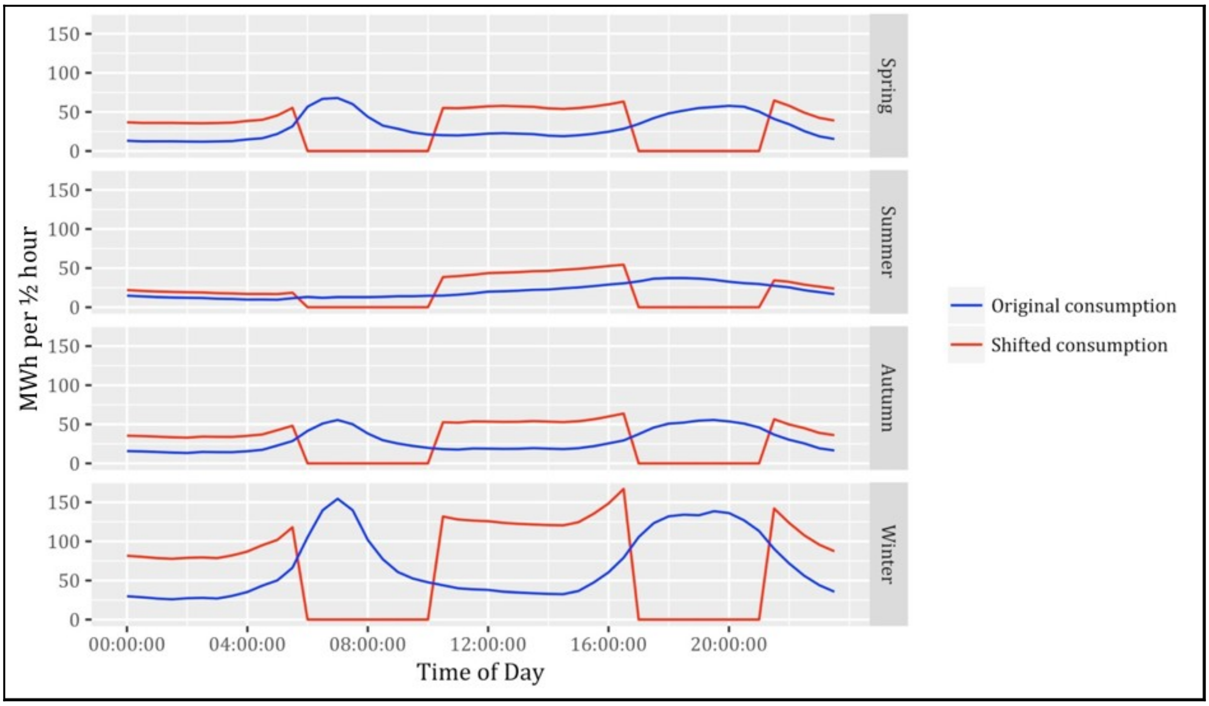
Graphic 4| HP SC1 total New Zealand energy consumption per season in GWh



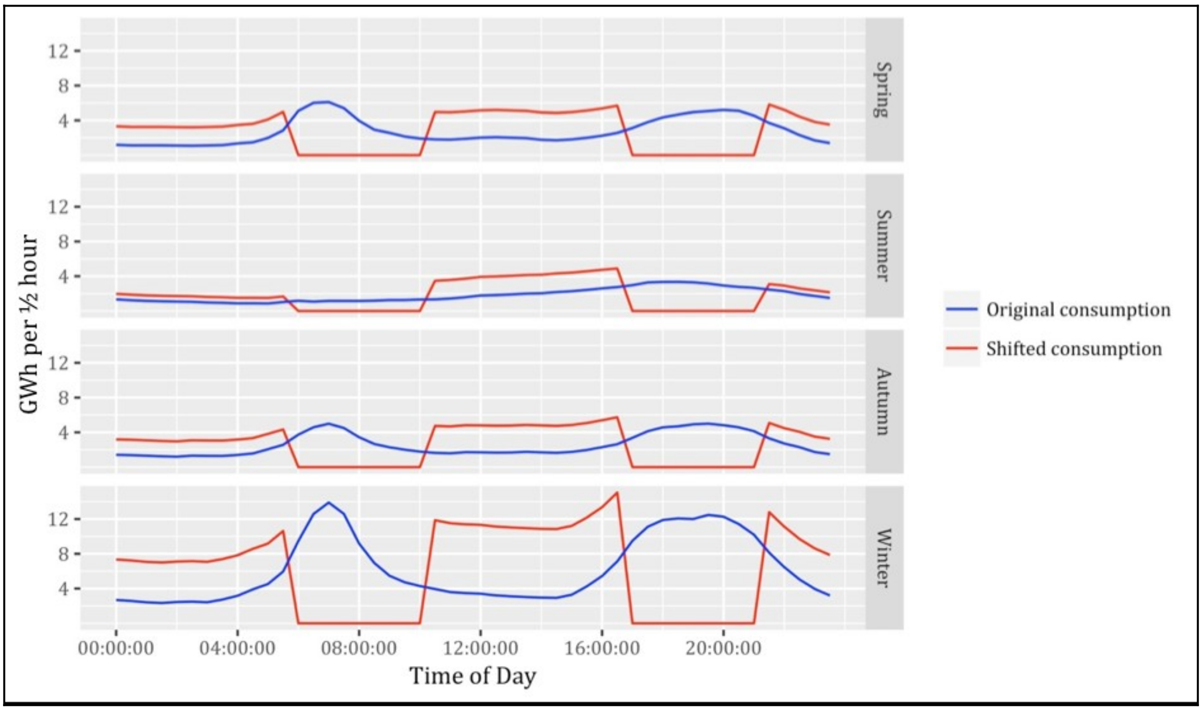
Graphic 5| HP SC2 total New Zealand energy consumption per day in MWh



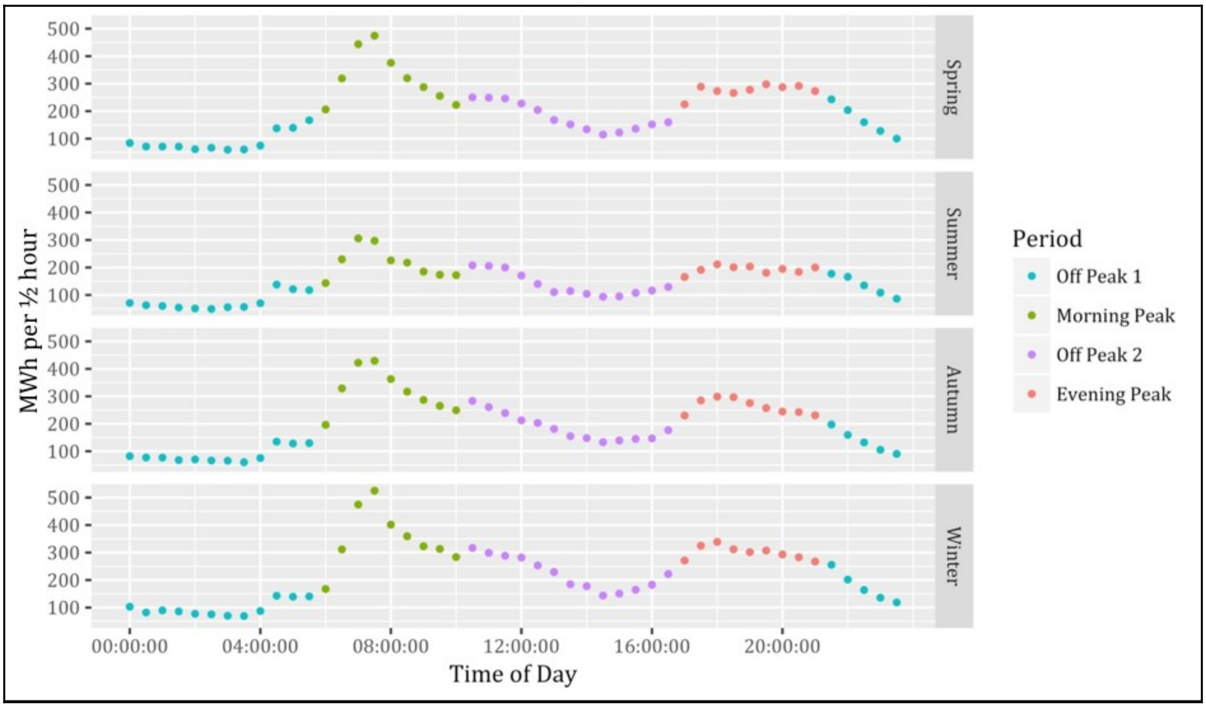
Graphic 6| HP SC2 total New Zealand energy consumption per season in GWh



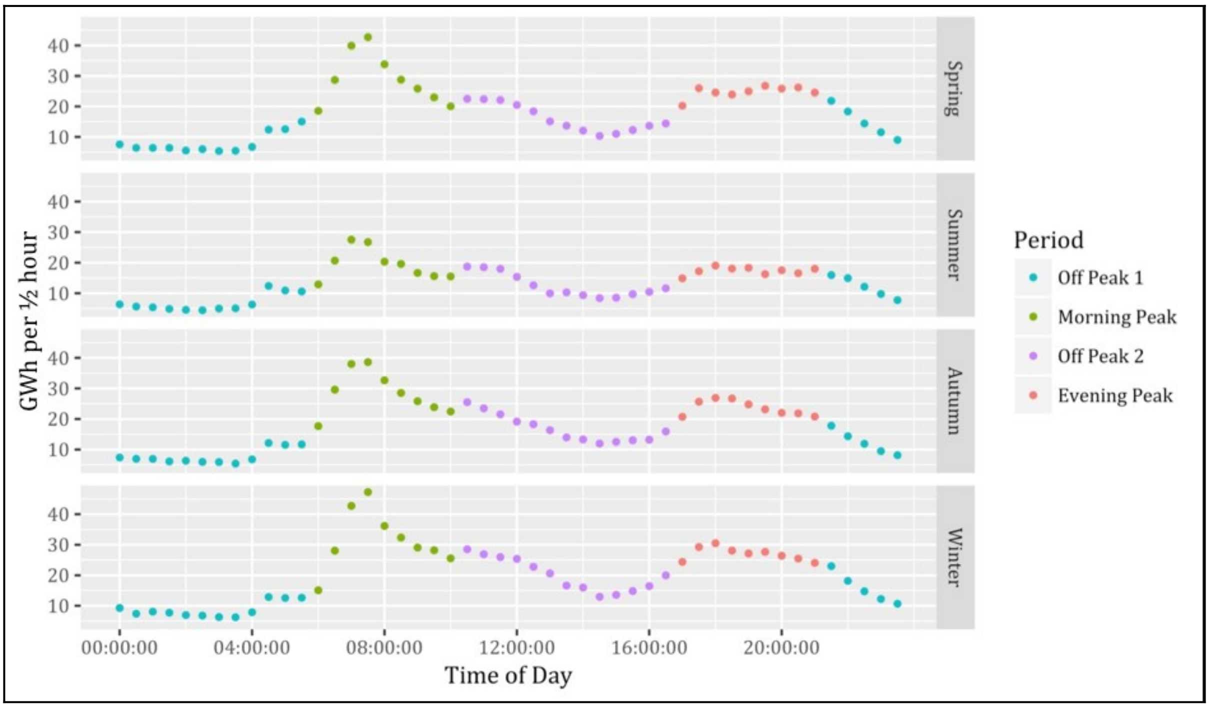
Graphic 7| HP SC3 total energy consumption New Zealand per day in MWh



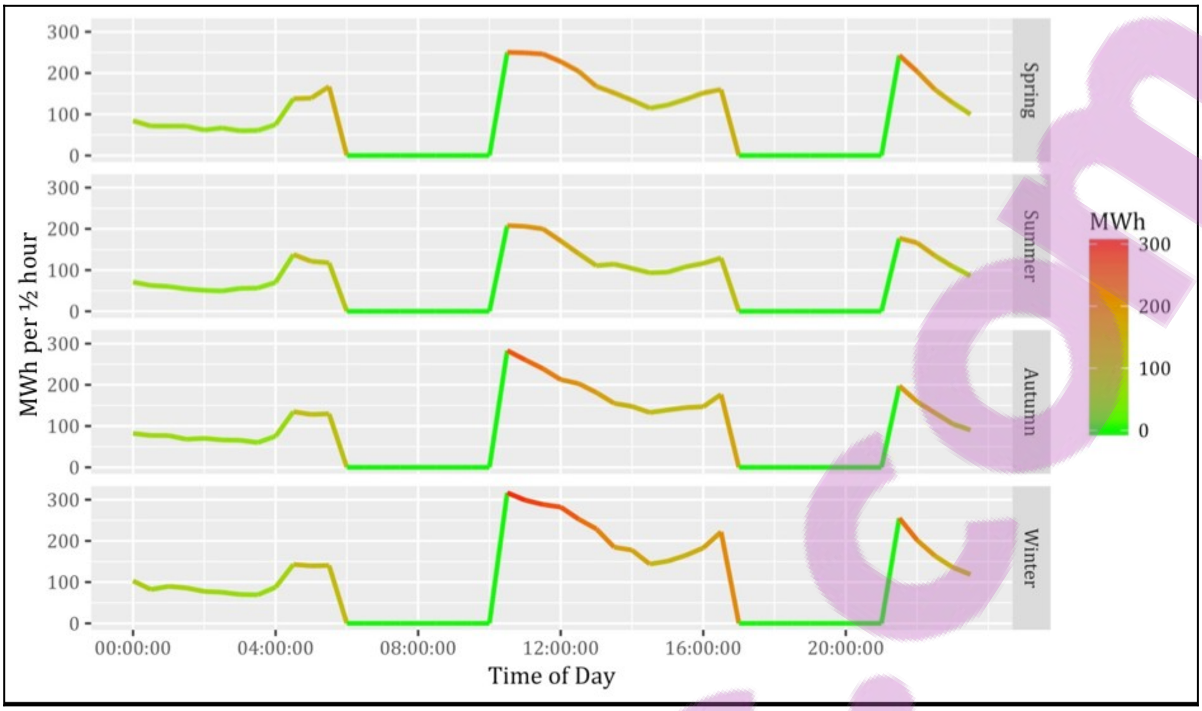
Graphic 8| HP SC3 total energy consumption New Zealand per season in GWh



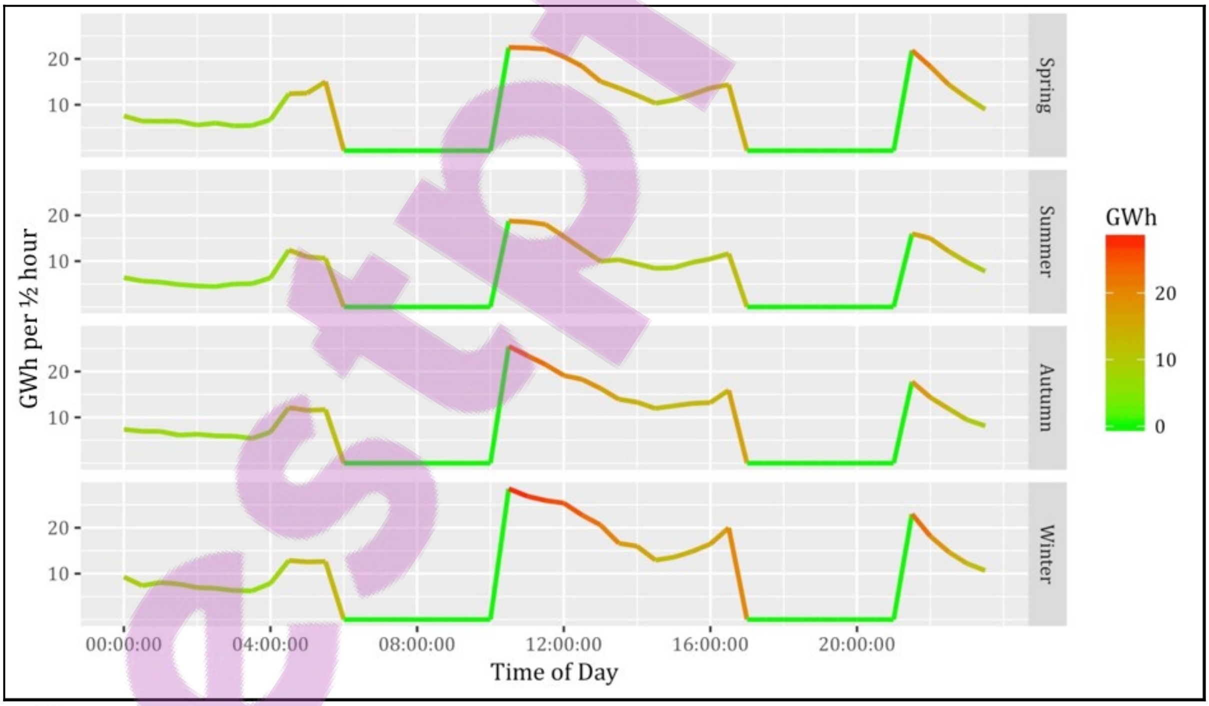
Graphic 9| HW total energy consumption New Zealand per day in MWh



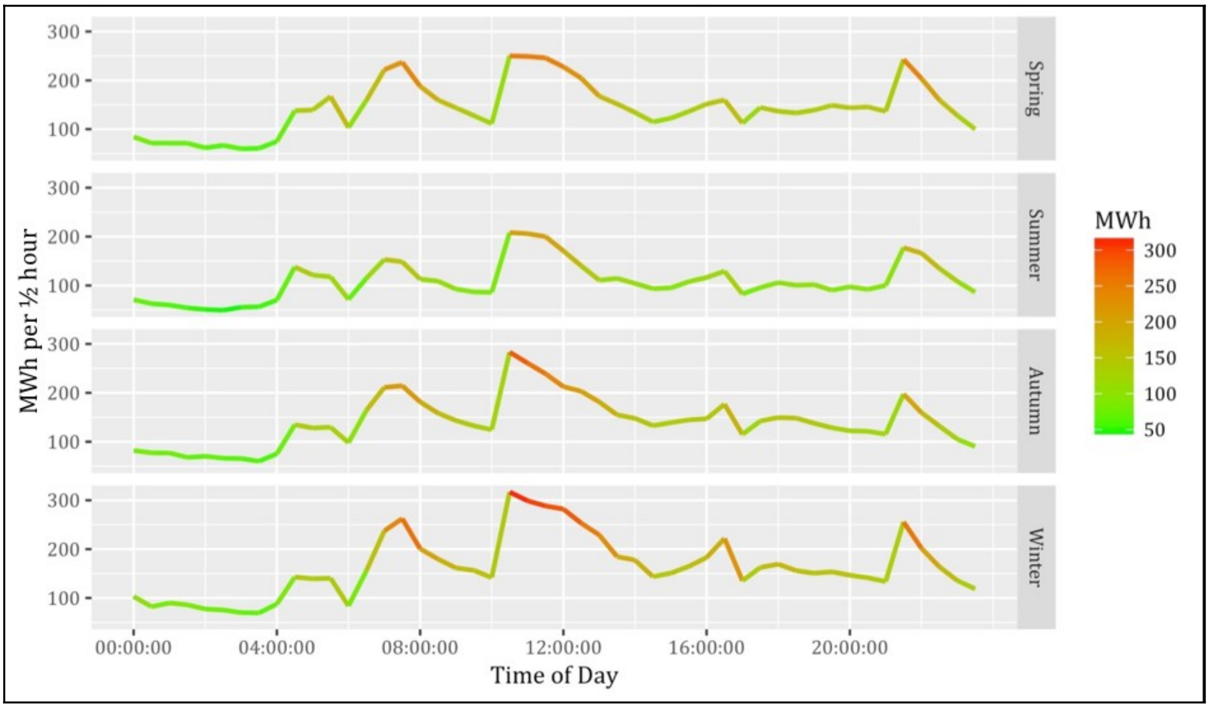
Graphic 10| HW total energy consumption New Zealand per season in GWh



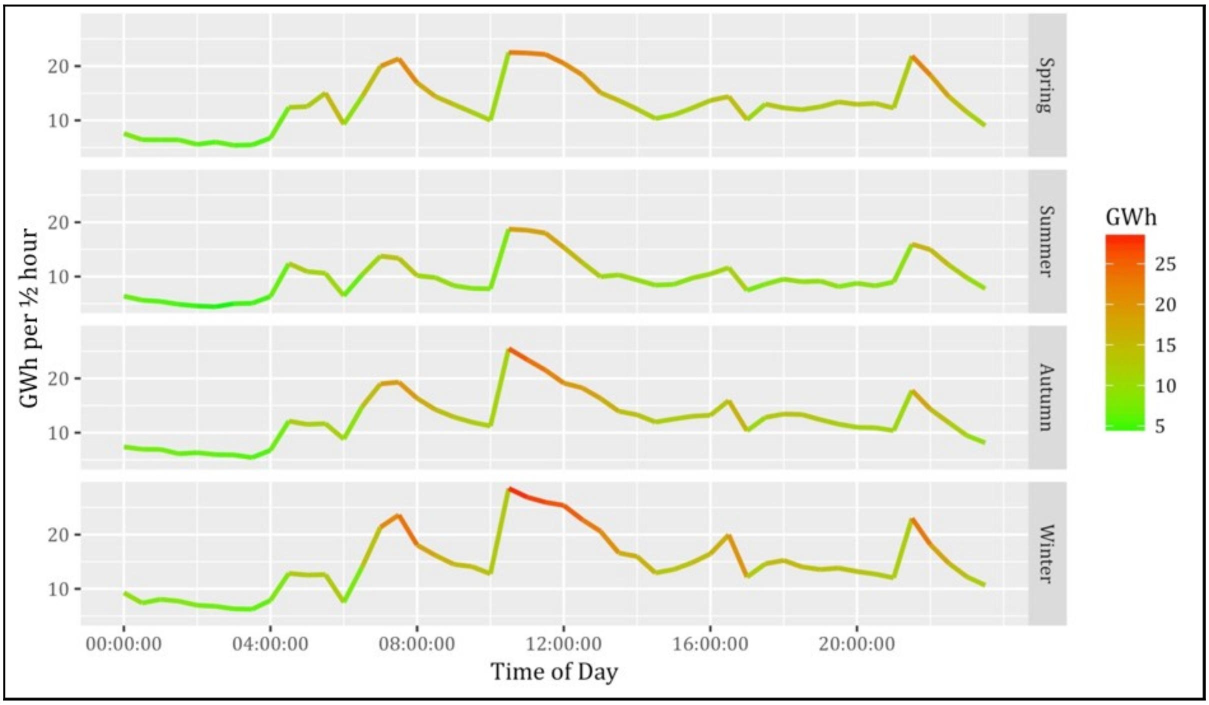
Graphic 11| HW SC1 total energy consumption New Zealand per day in MWh



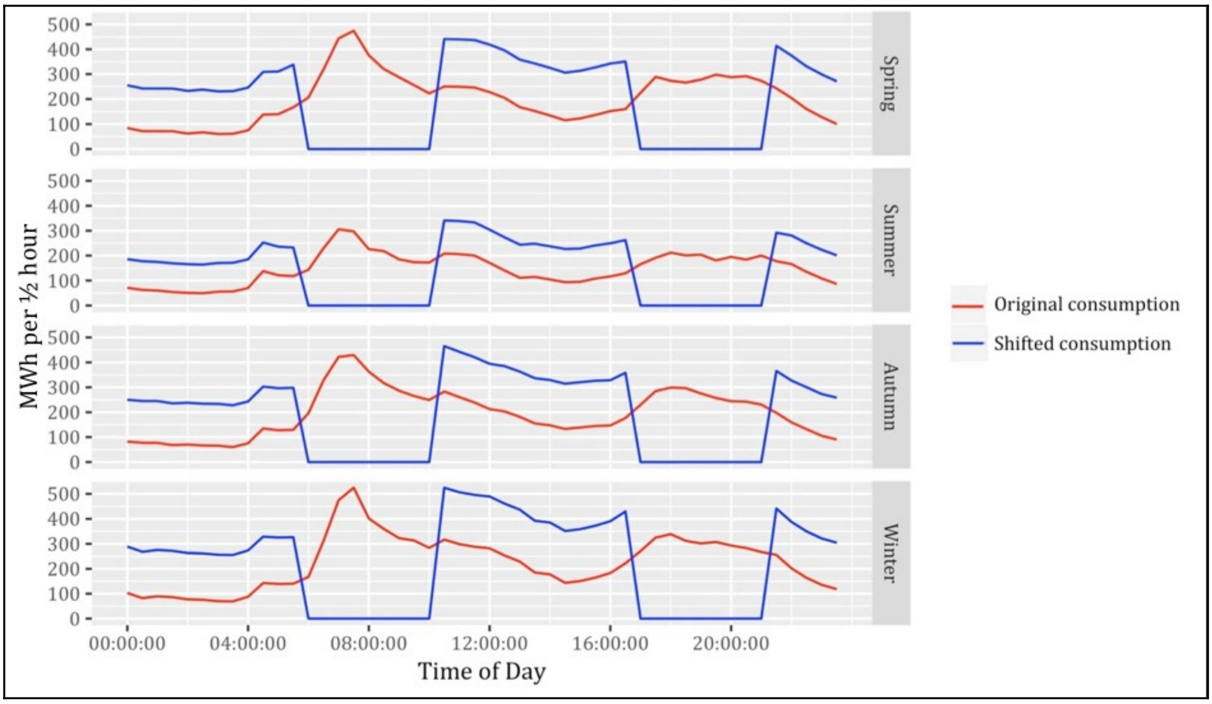
Graphic 12| HW SC1 total energy consumption New Zealand per season in GWh



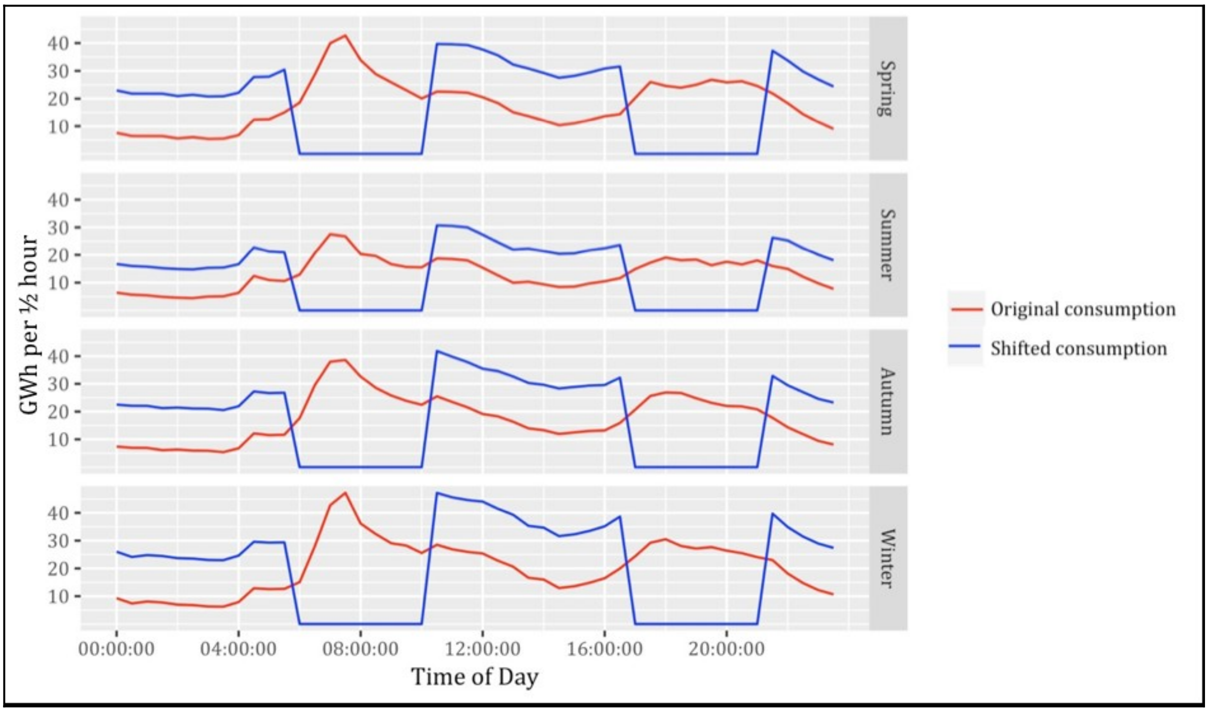
Graphic 13| HW SC2 total energy consumption New Zealand per day in MWh



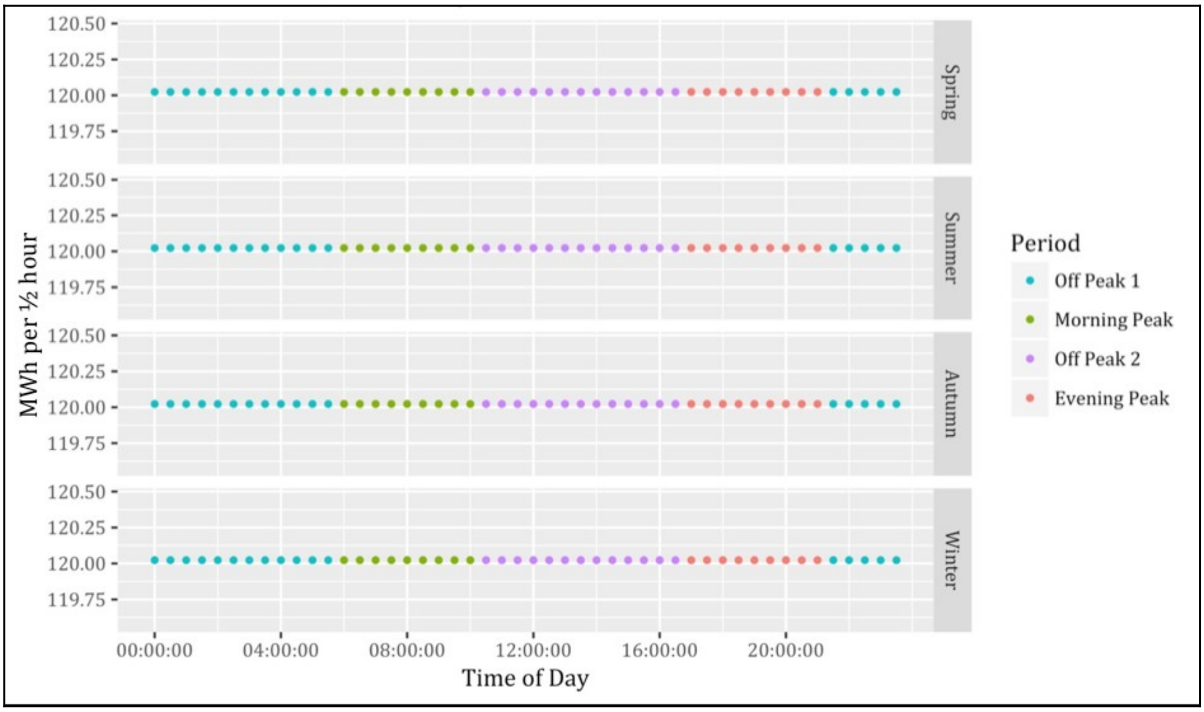
Graphic 14| HW SC2 total energy consumption New Zealand per season in GWh



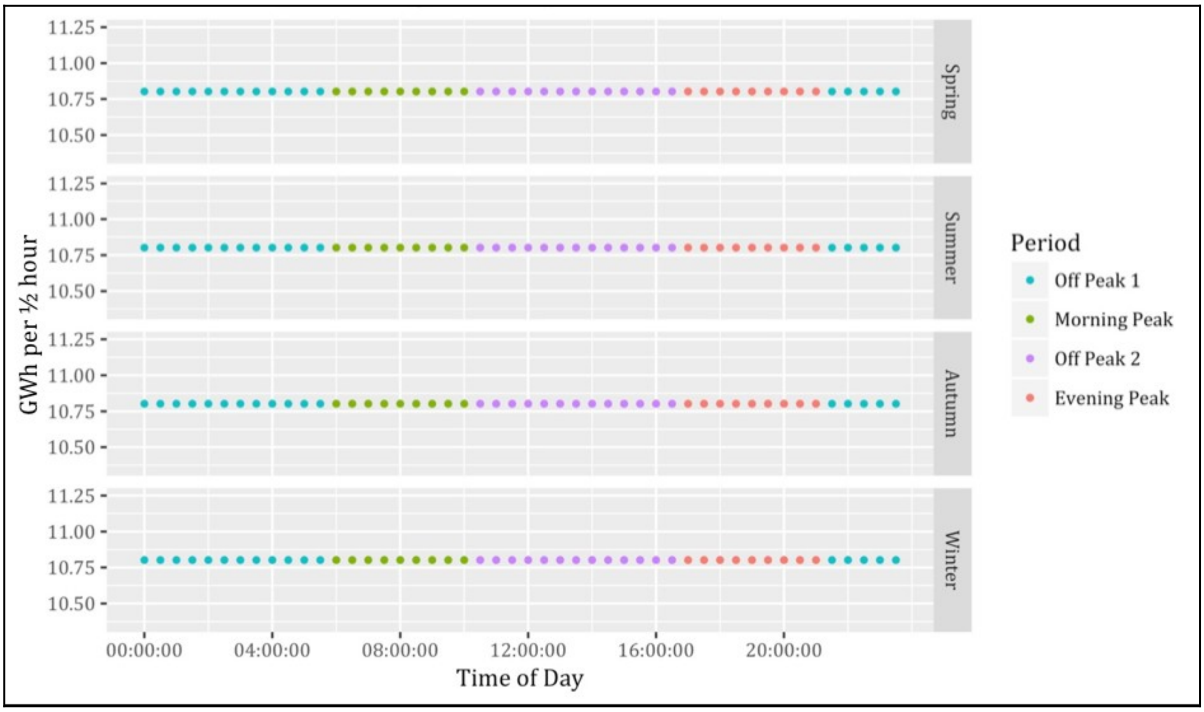
Graphic 15| HW SC3 total energy consumption New Zealand per day in MWh



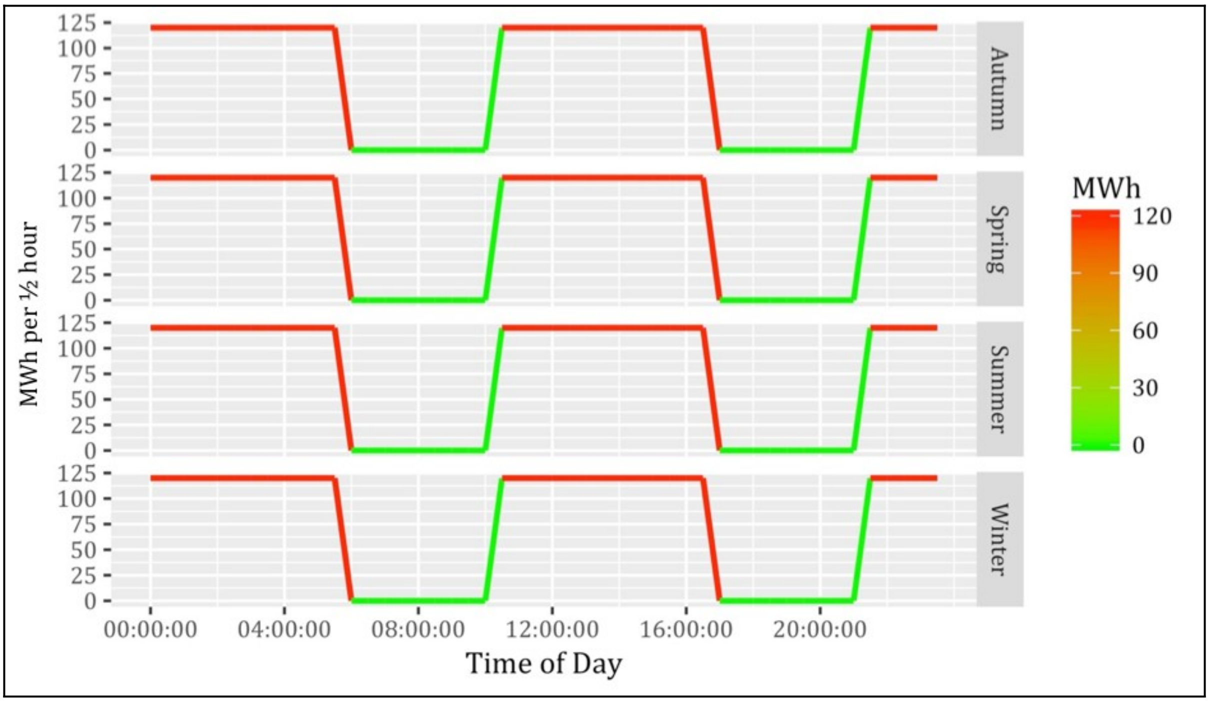
Graphic 16| HW SC3 total energy consumption New Zealand per season in GWh



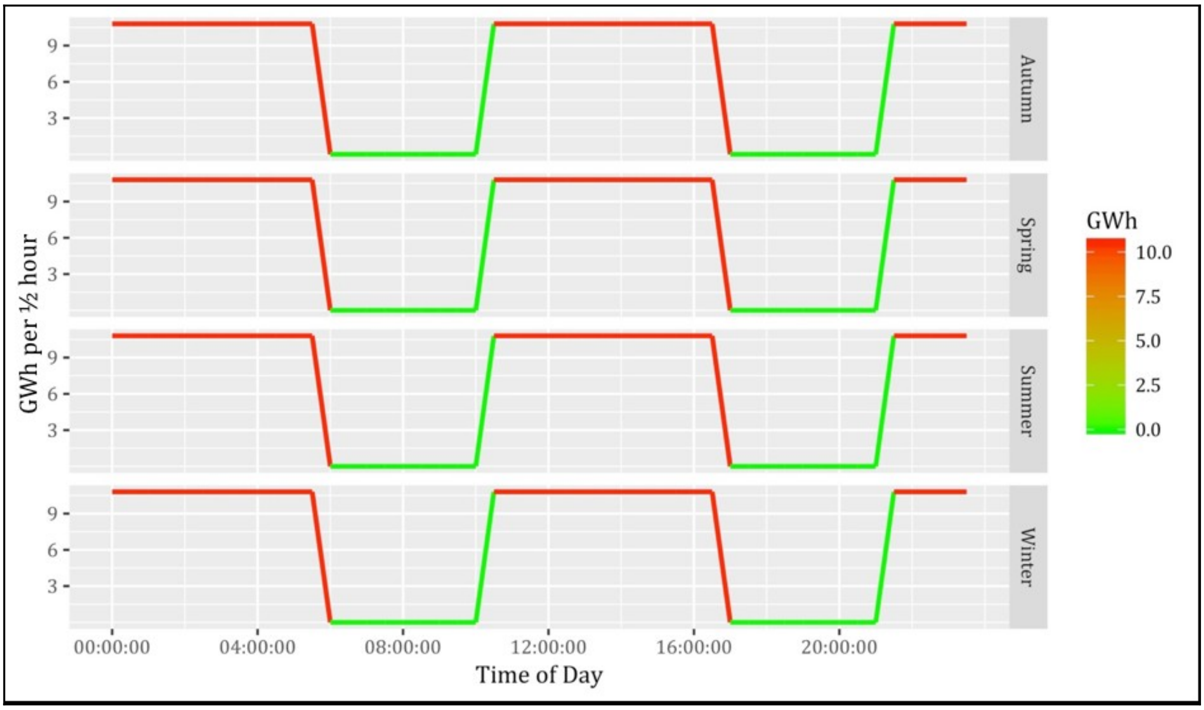
Graphic 17| REF total energy consumption New Zealand per day in MW



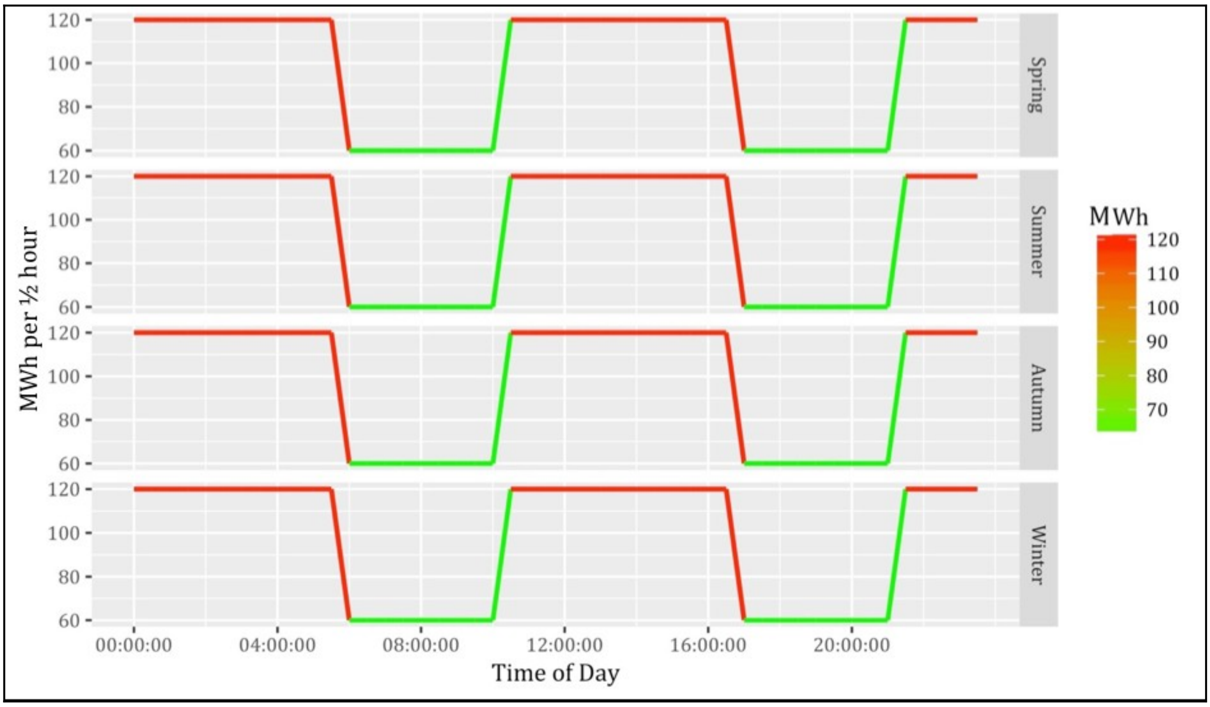
Graphic 18| REF total energy consumption New Zealand per season in GWh



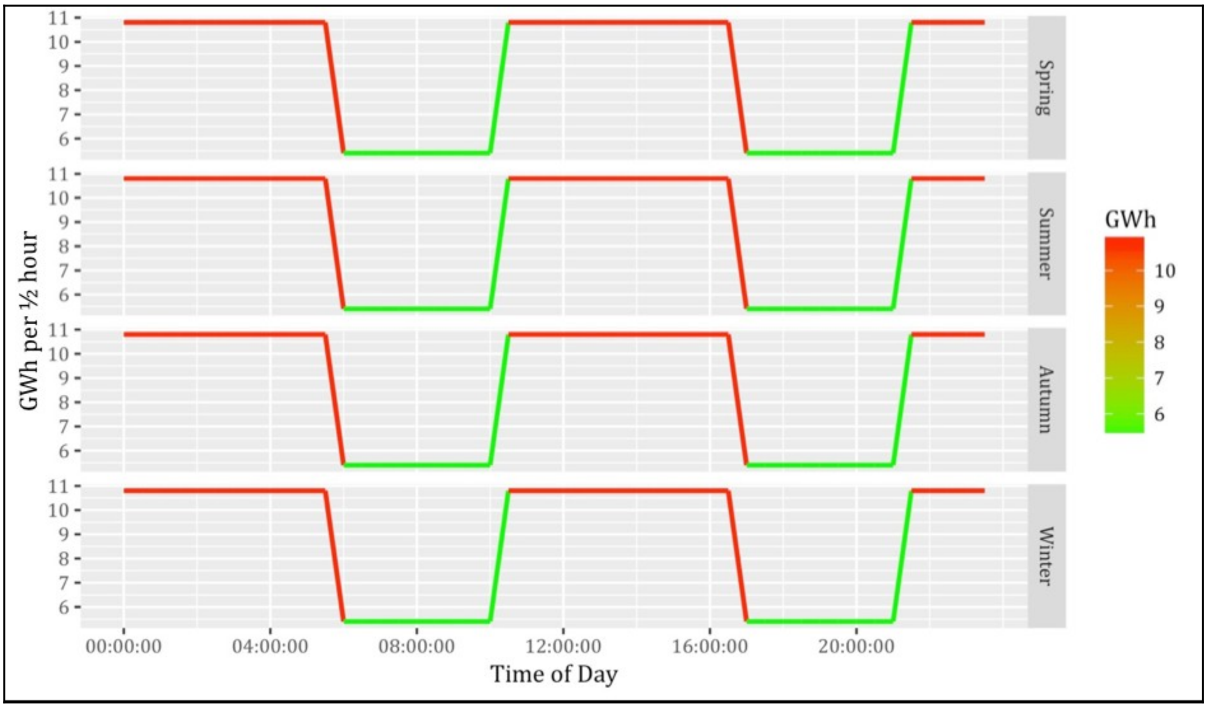
Graphic 19| REF SC1 total energy consumption New Zealand per day in MWh



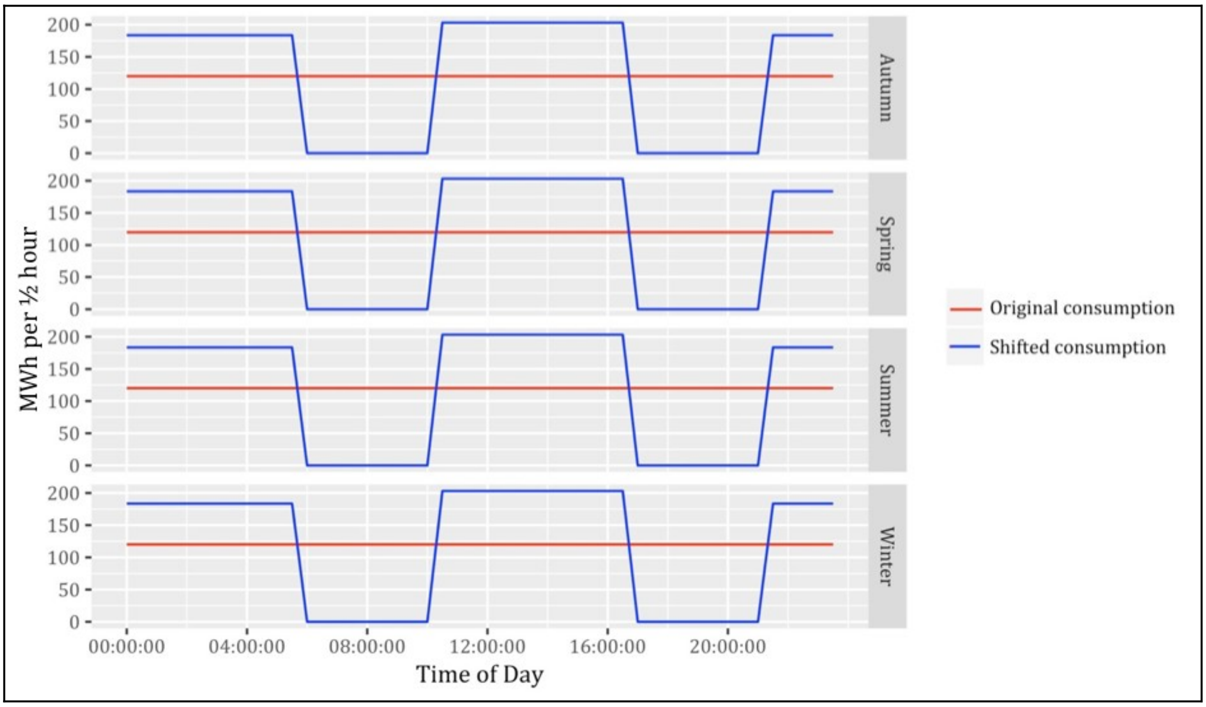
Graphic 20| REF SC1 total energy consumption New Zealand per season in GWh



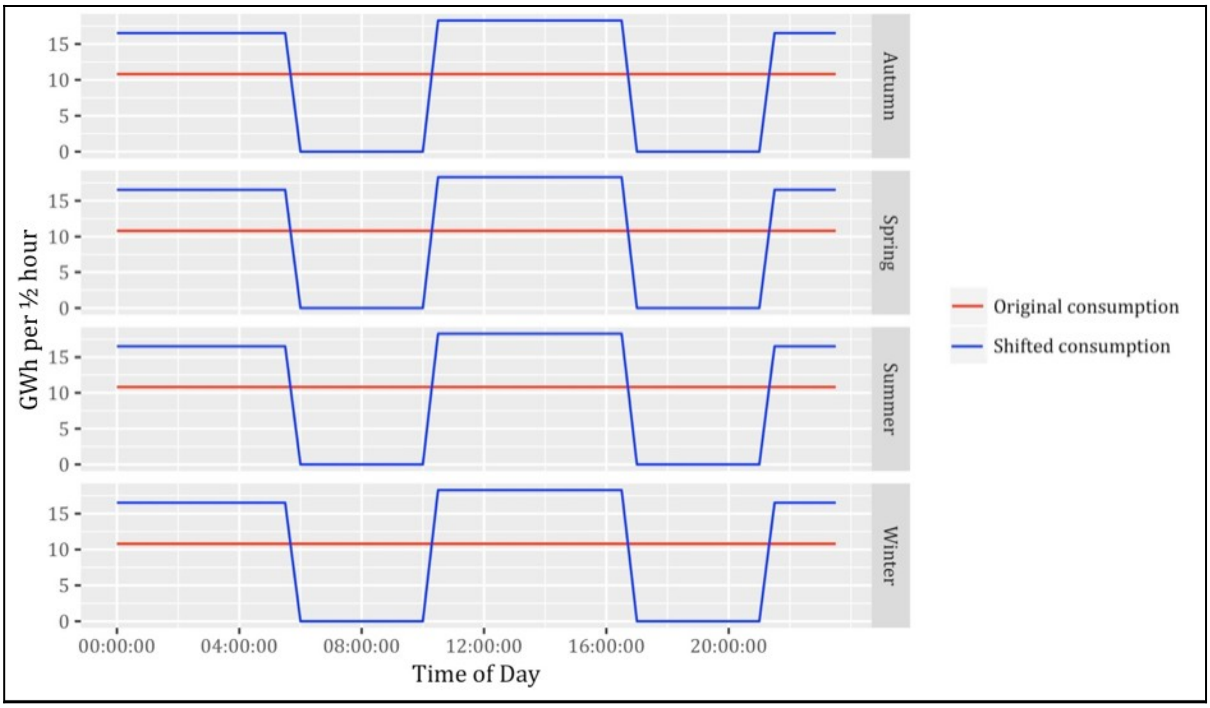
Graphic 21| REF SC2 total energy consumption New Zealand per day in MWh



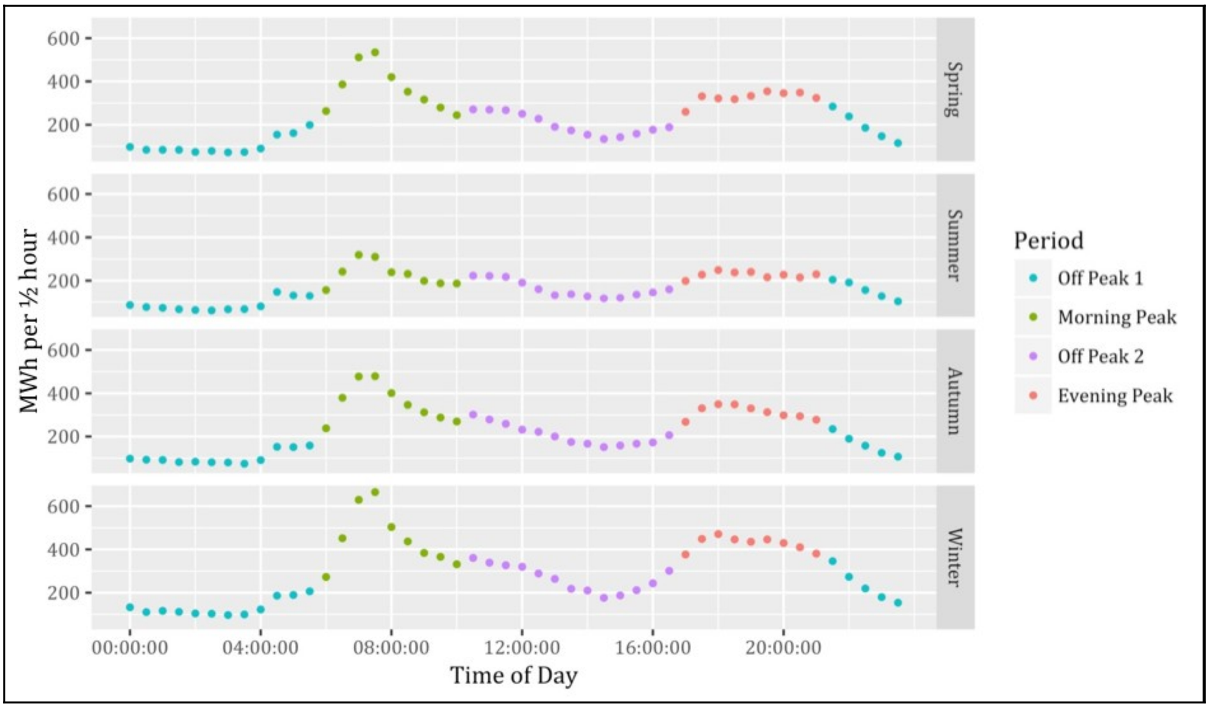
Graphic 22| REF SC2 total energy consumption New Zealand per season in GWh



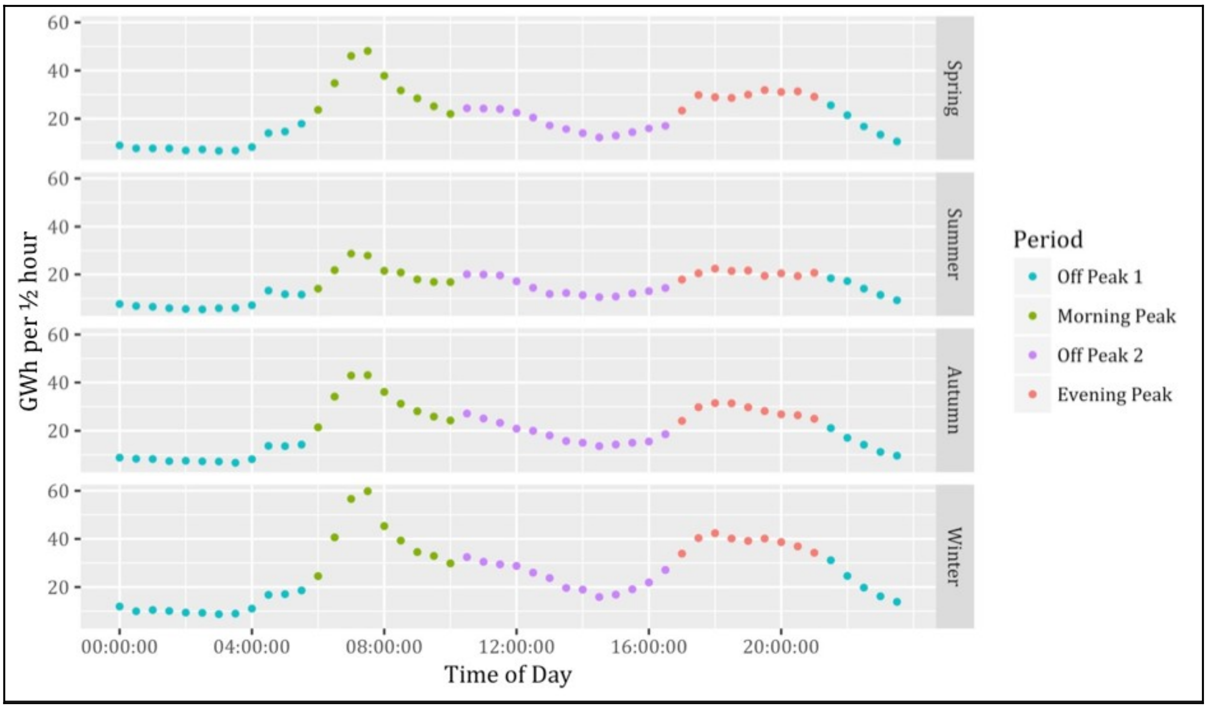
Graphic 23| REF SC3 total energy consumption New Zealand per day in MWh



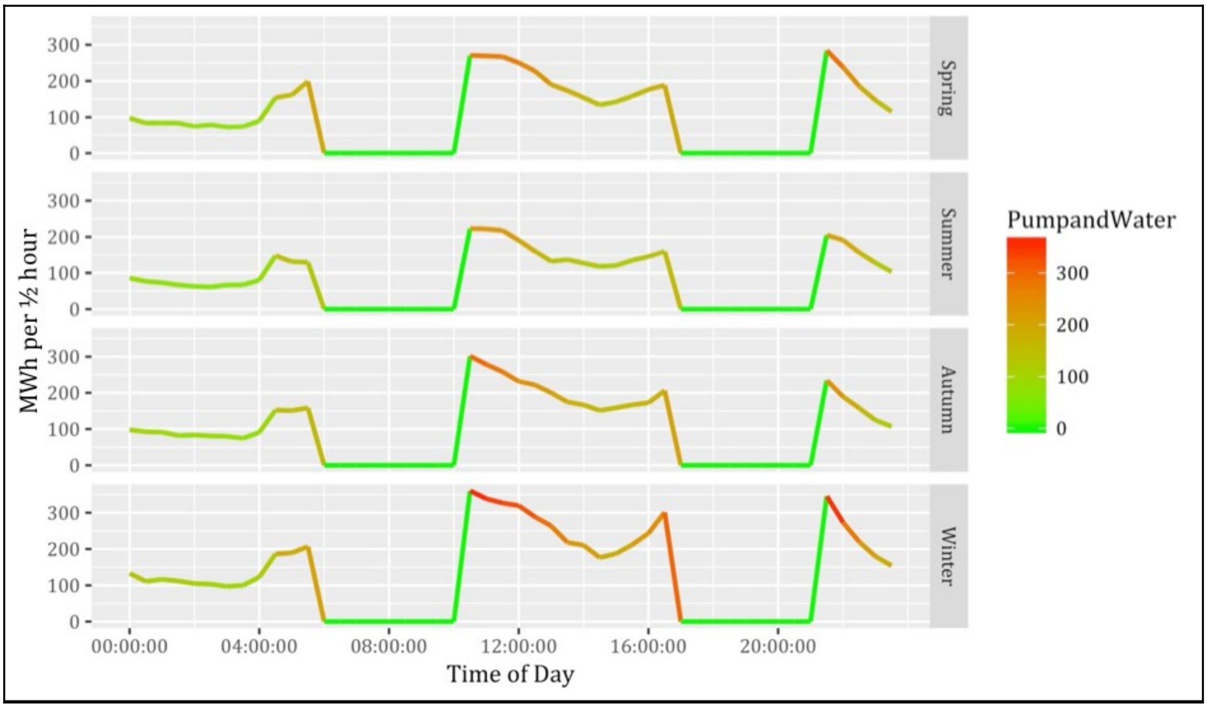
Graphic 24| REF SC3 total energy consumption New Zealand per season in GWh



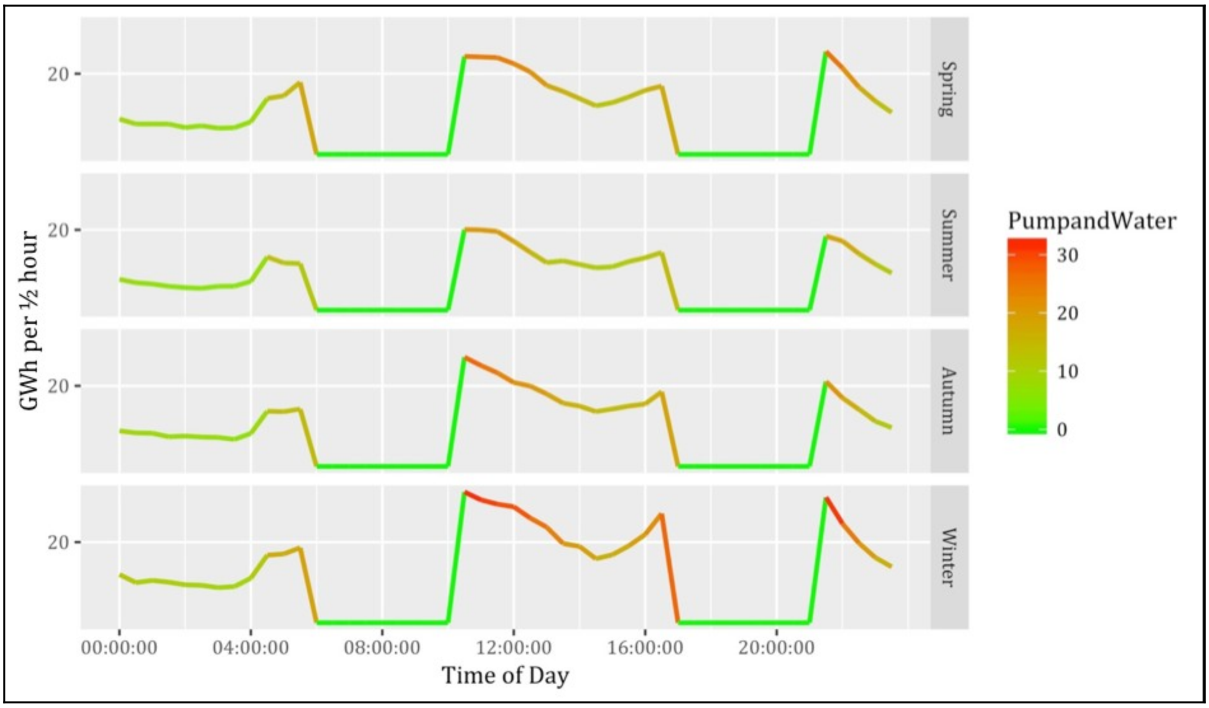
Graphic 25| HP&HW total New Zealand energy consumption per day in MWh



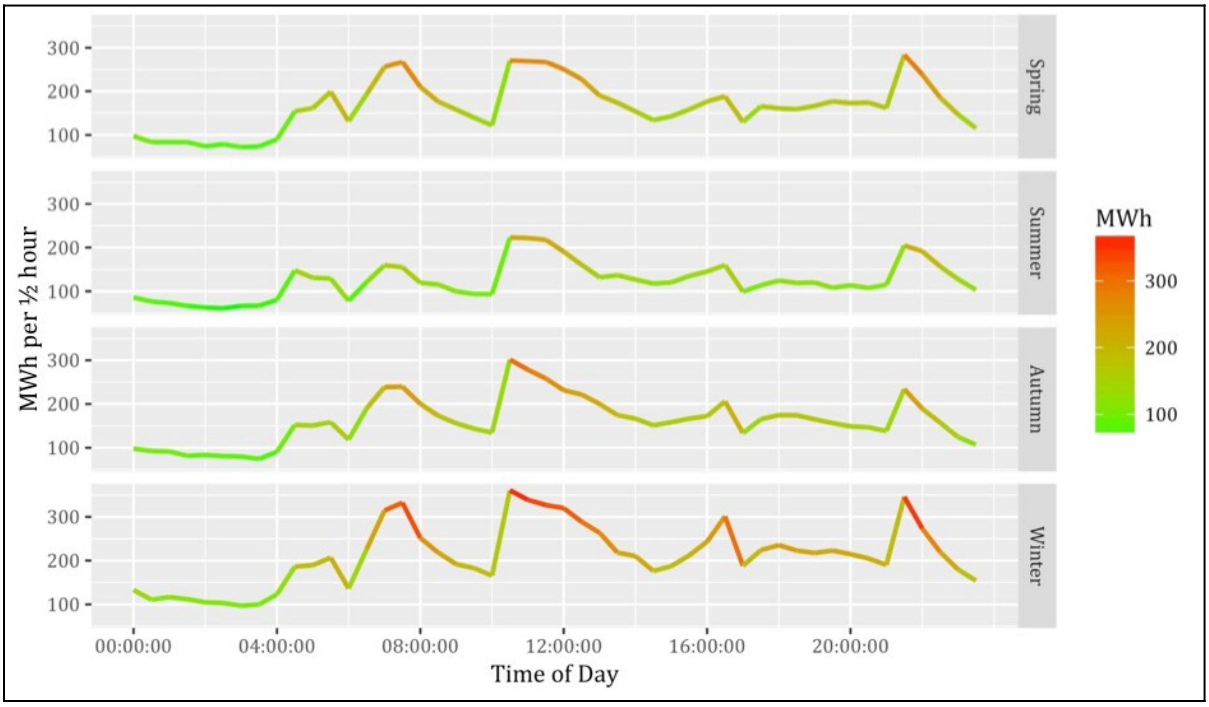
Graphic 26| HP&HW total New Zealand energy consumption per season in GWh



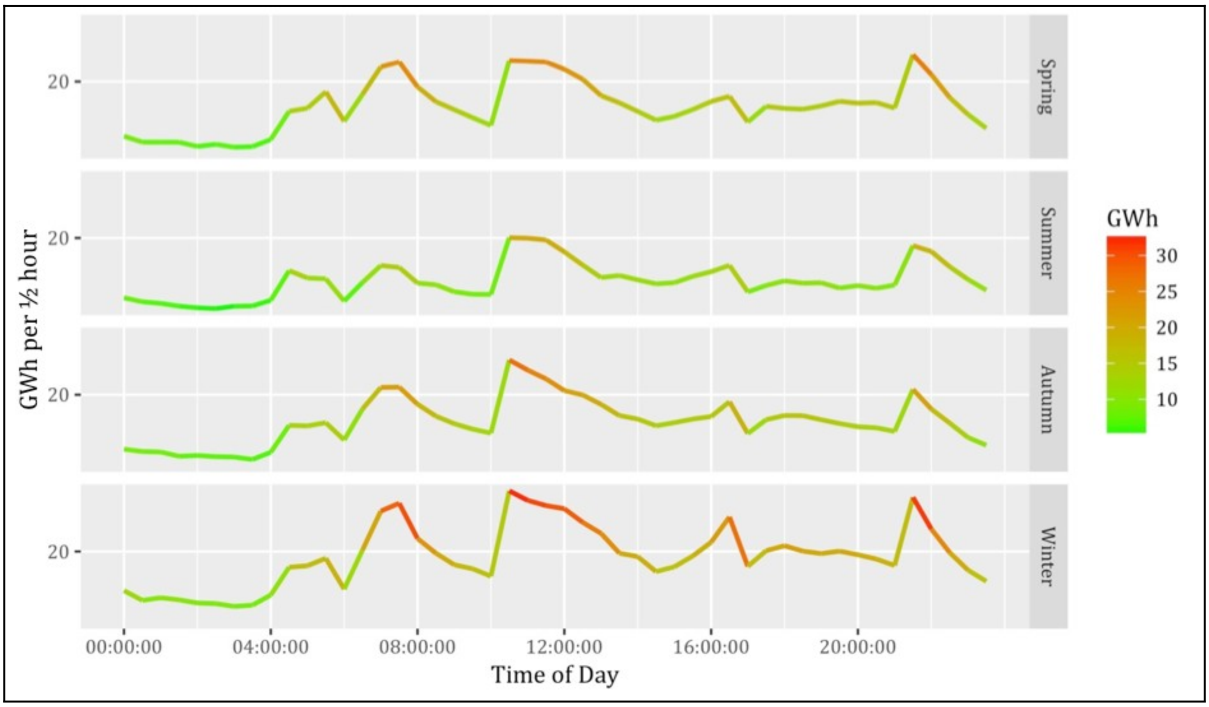
Graphic 27| HP&HW SC1 total New Zealand energy consumption per day in MWh



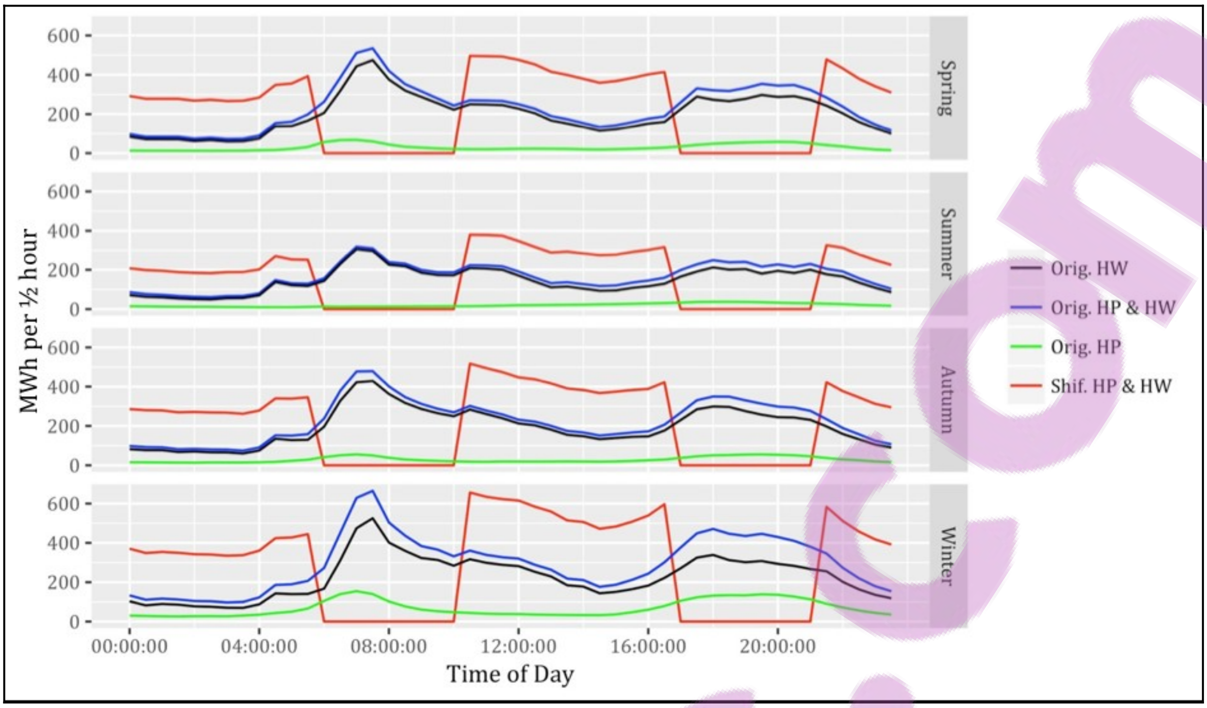
Graphic 28| HP&HW SC1 total New Zealand energy consumption per season in GWh



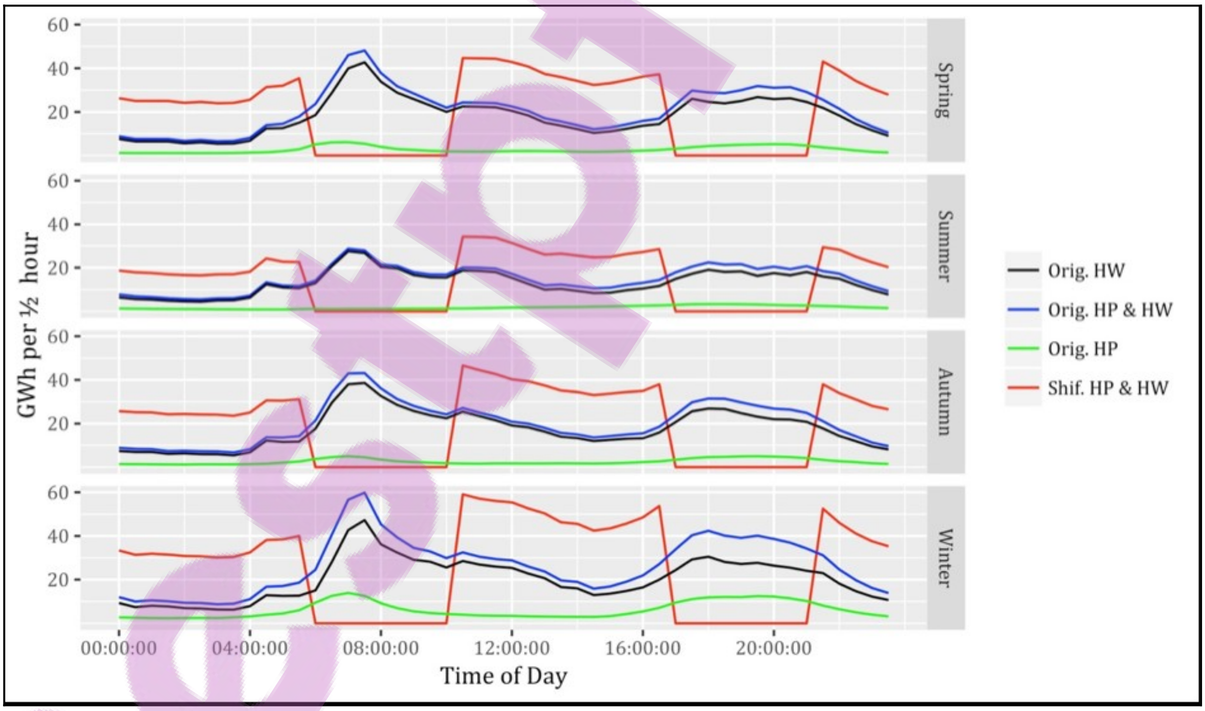
Graphic 29| HP&HW SC2 total New Zealand energy consumption per day in MWh



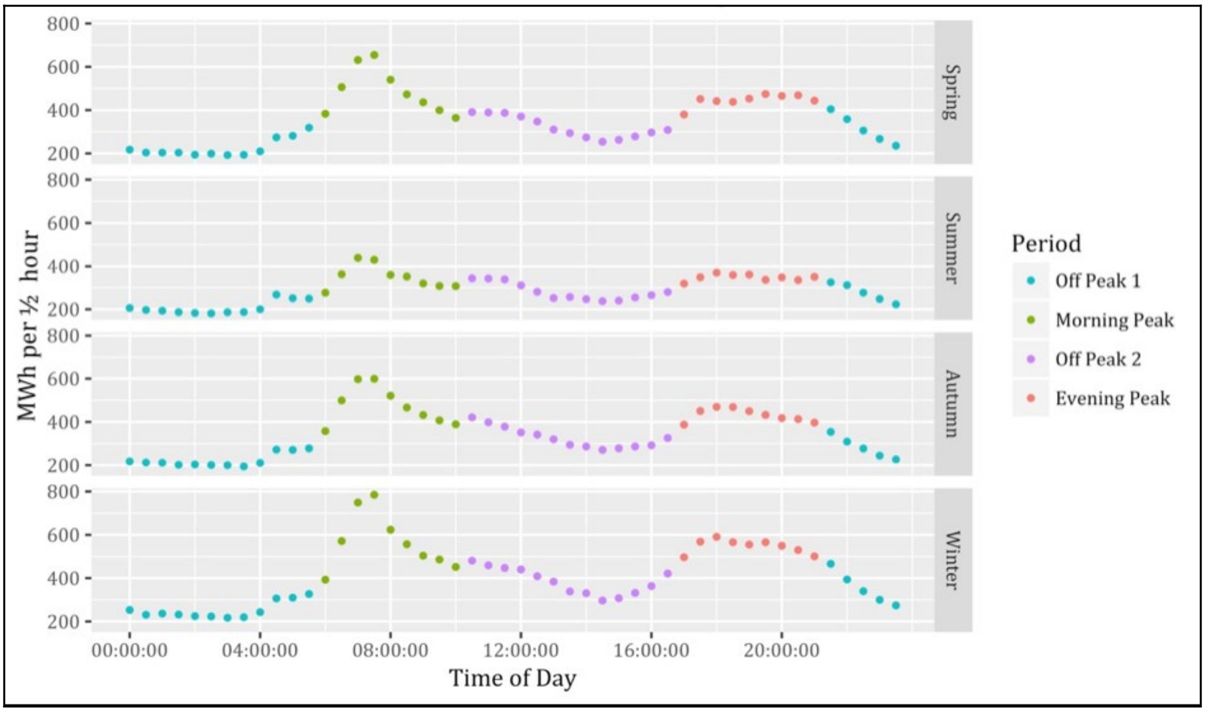
Graphic 30| HP&HW SC2 total New Zealand energy consumption per season in GWh



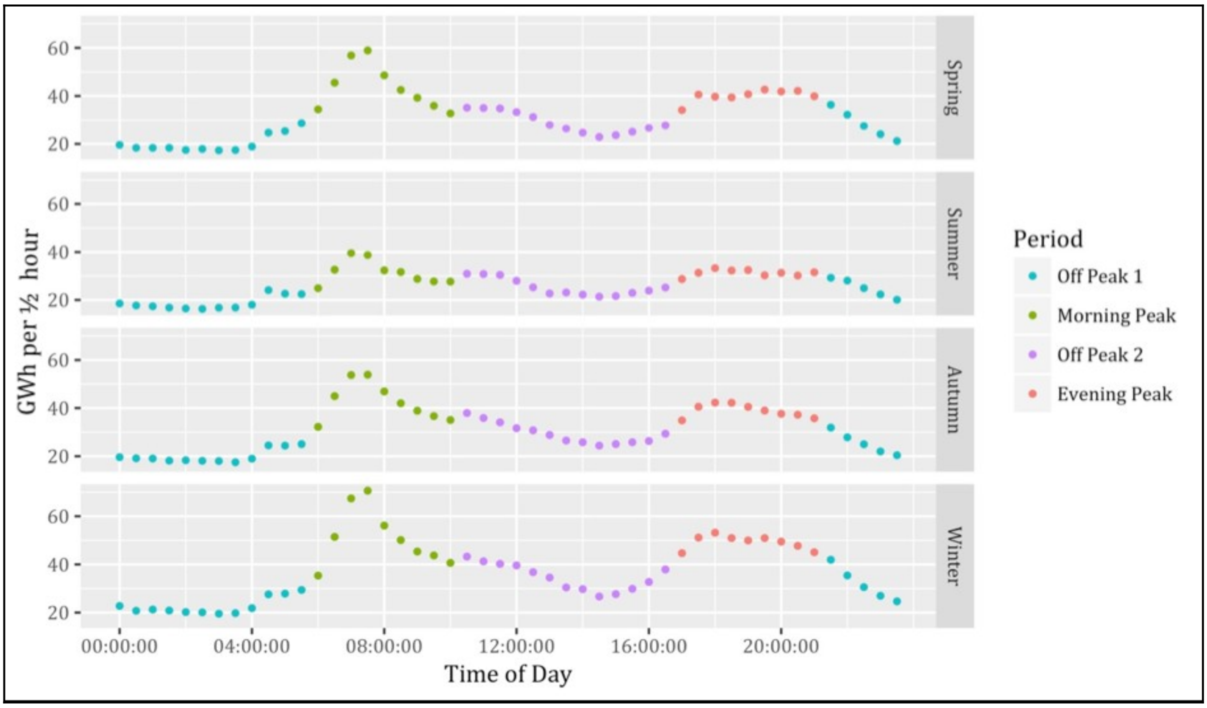
Graphic 31| HP&HW SC3 total New Zealand energy consumption per day in MWh



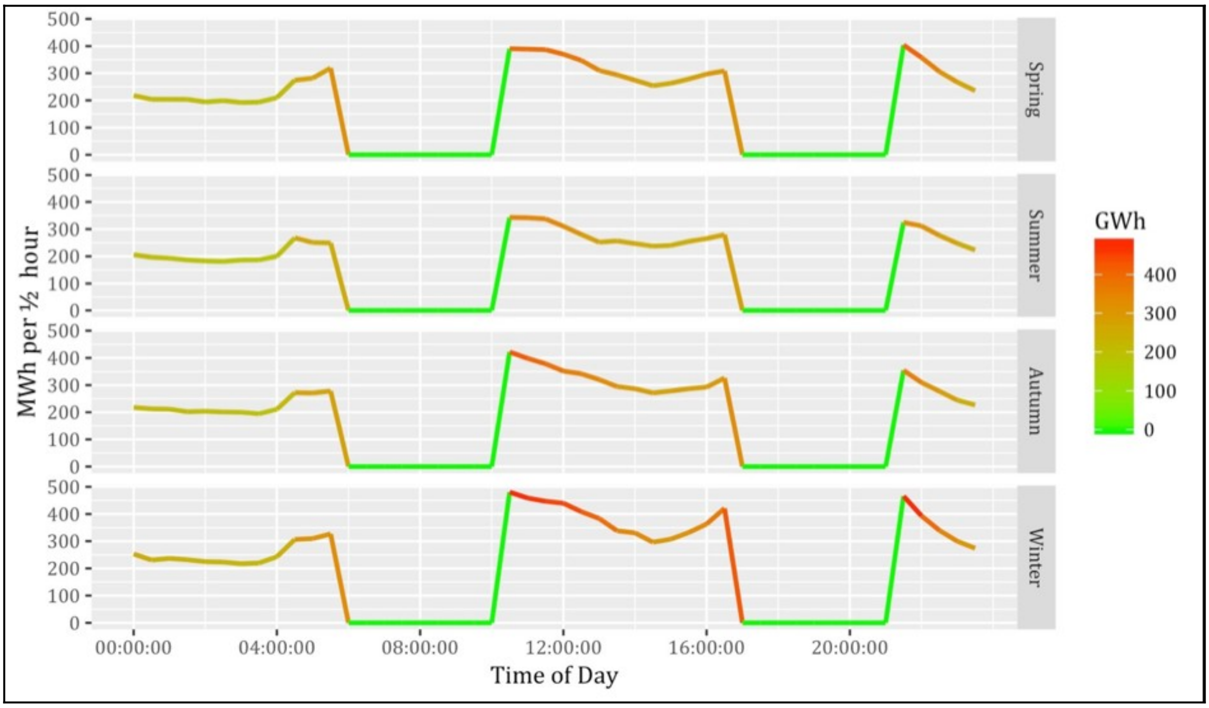
Graphic 32| HP&HW SC3 total New Zealand energy consumption per season in GWh



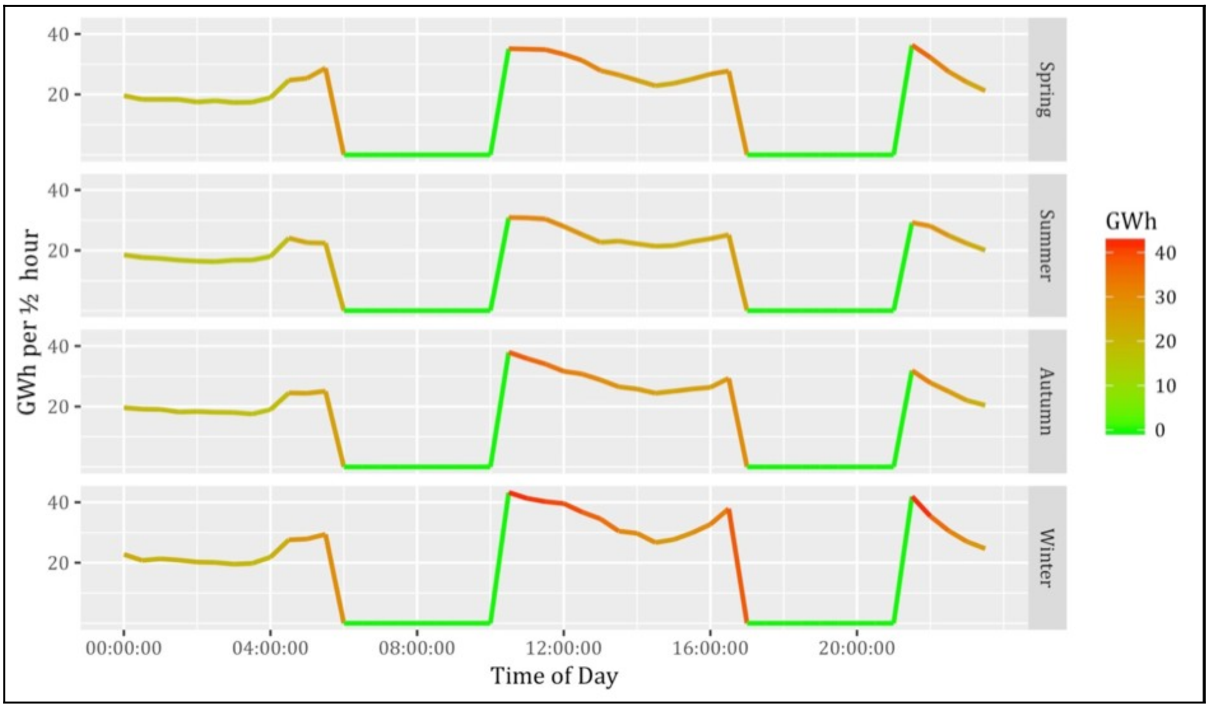
Graphic 33| HP, HW&REF total New Zealand energy consumption per day in MWh



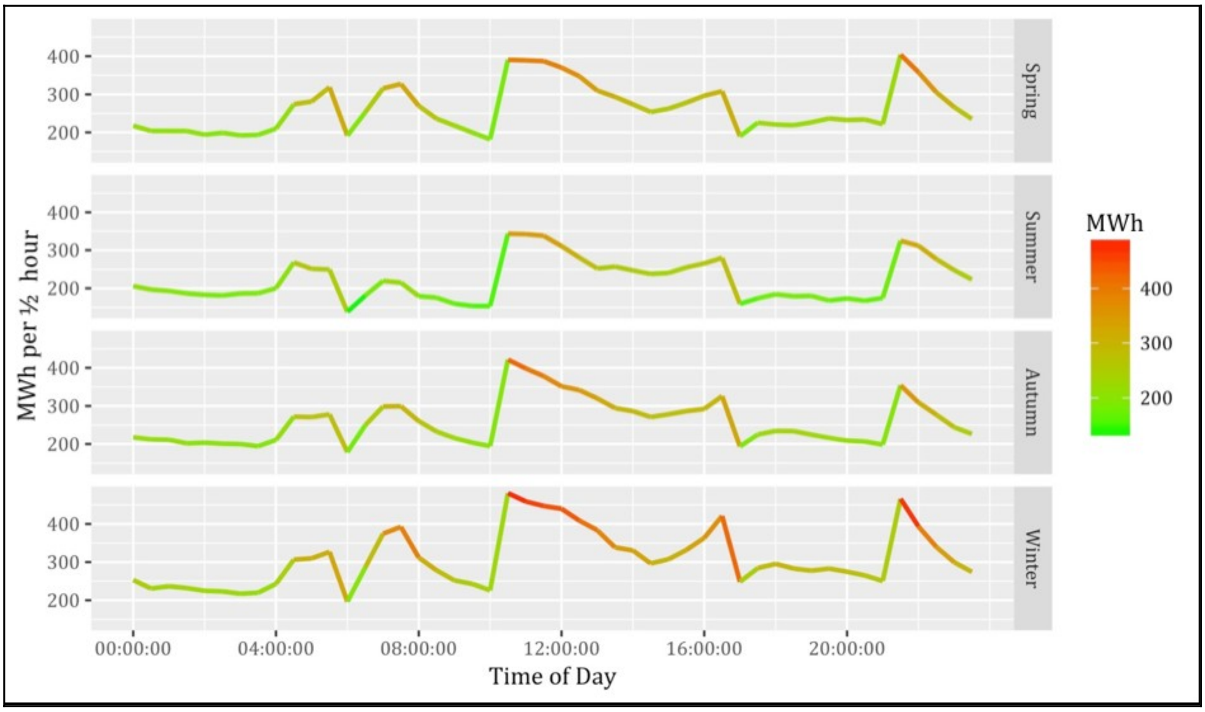
Graphic 34| HP, HW&REF total New Zealand energy consumption per season in GWh



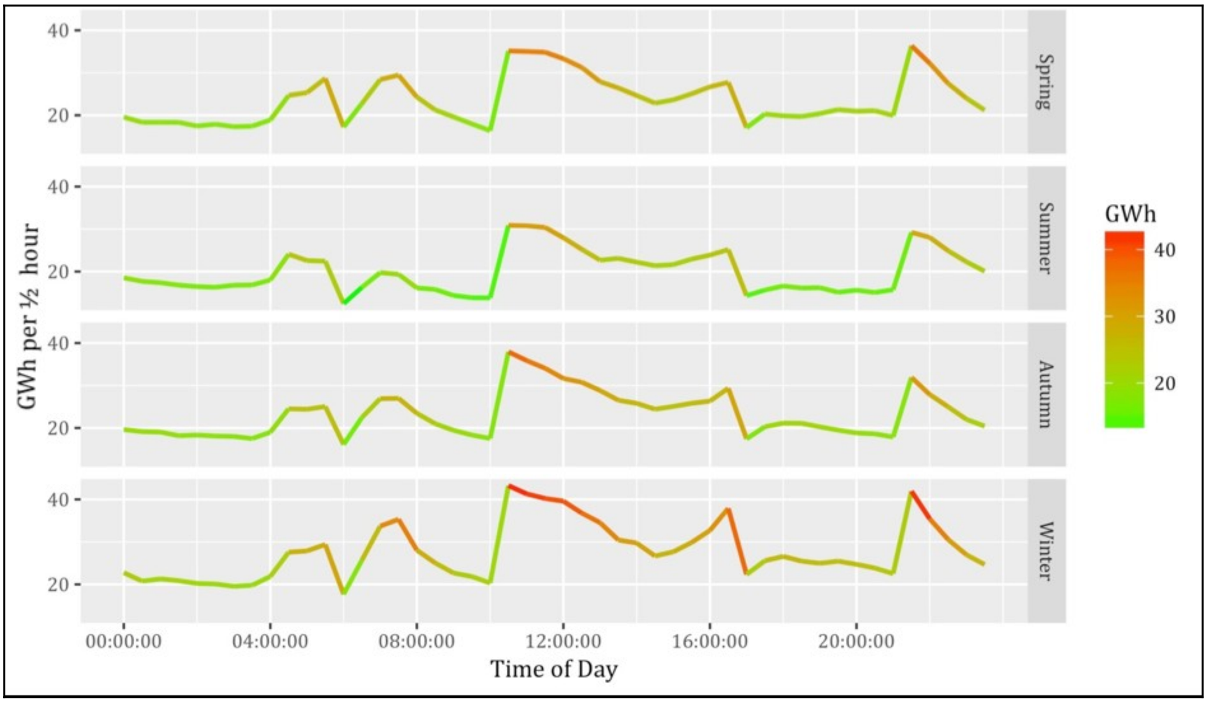
Graphic 35| HP, HW&REF SC1 total New Zealand energy consumption per day in MWh



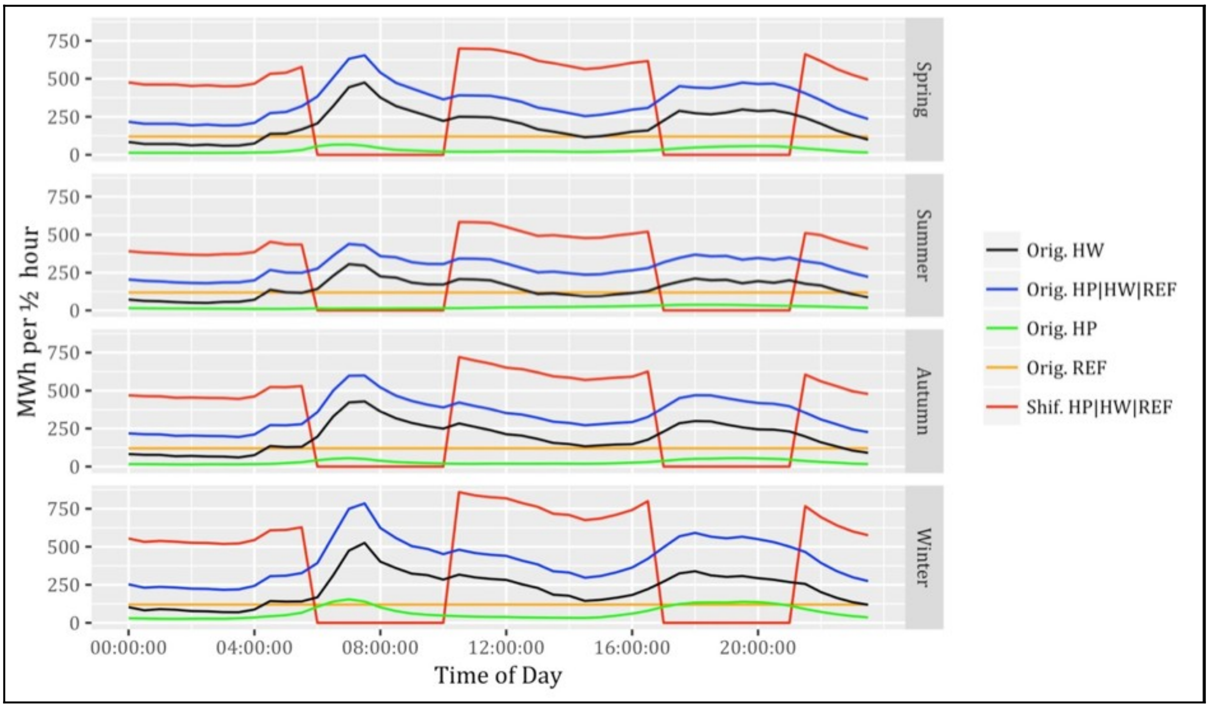
Graphic 36| HP, HW&REF SC1 total New Zealand energy consumption per season in GWh



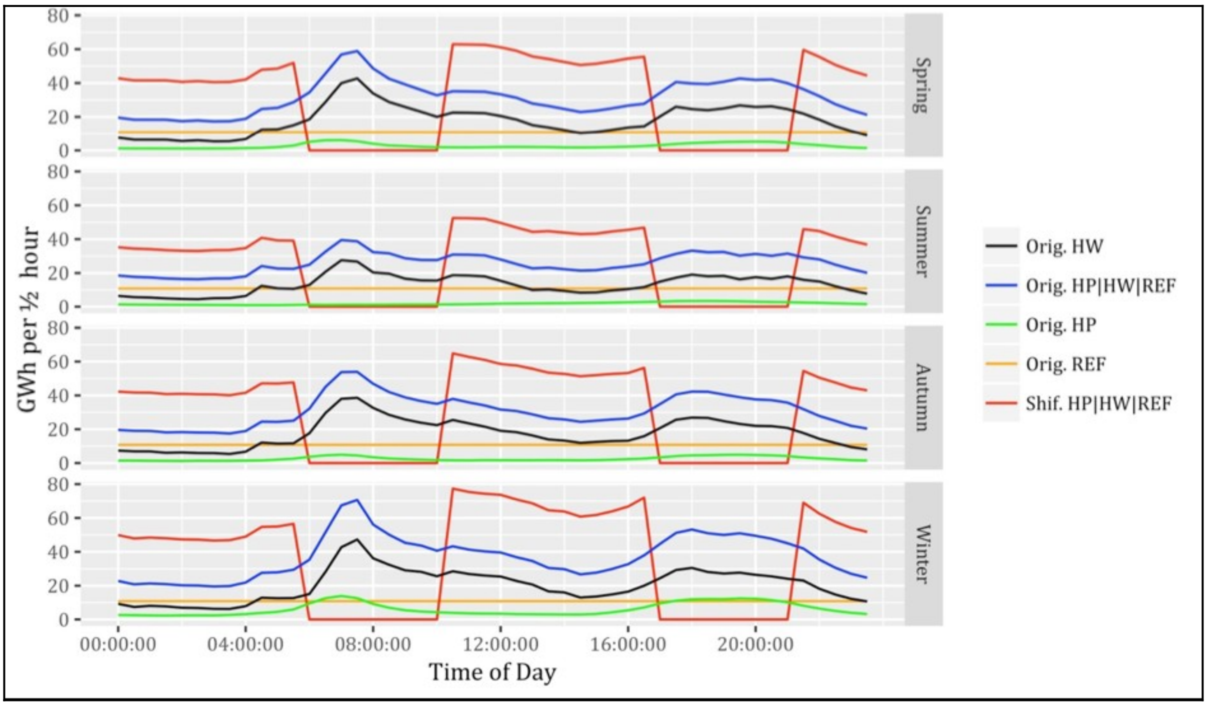
Graphic 37| HP, HW&REF SC2 total New Zealand energy consumption per day in MWh



Graphic 38| HP, HW&REF SC2 total New Zealand energy consumption per season in GWh



Graphic 39| HP, HW&REF SC3 total New Zealand energy consumption per day in MWh



Graphic 40| HP, HW&REF SC3 total New Zealand energy consumption per season in GWh

End of Report