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# Scenario Analysis of Residential Demand Response at Network Peak Periods

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## **Abstract**

Electricity demand response refers to consumer actions that change the utility load profile in a way that reduces costs or improves grid security. Residential demand response (RDR) can be treated as an energy resource which can be assessed and commercially developed. RDR prospectors require more detailed information about usage patterns and penetration for specific electrical appliances during system peak load. The electric utilities normally measure electricity consumption data aggregated over many households and other users on a feeder and do not have information on household end-use behaviour. This paper describes a bottom-up diversified demand model that can be used to estimate load profile of residential customers in a given region. The model has been calibrated by a stated preference demand response survey and used to estimate the voluntary demand response potential for the residential customers in Christchurch, New Zealand, where winter peak demand is becoming increasingly difficult to meet on a capacity-constrained network.

**Key Words:** Residential peak demand, Demand response behaviour, Demand side management, Demand response modelling.

## **1. Introduction**

The growth in peak demand causes a strain on the available power generation, transmission and distribution infrastructure, and meeting this peak demand is often associated with high cost. The goal of demand response is to reduce or shift electricity usage from the peak period through the use of specially designed programs. Demand response projects aimed at reducing peak load have historically been limited to large industrial and commercial users. The residential sector contribution to the system peak load can be substantial and has been the subject of discussion internationally. A study done in New Zealand in 2007, for example, attributed about half of the system peak load to residential customers [1].

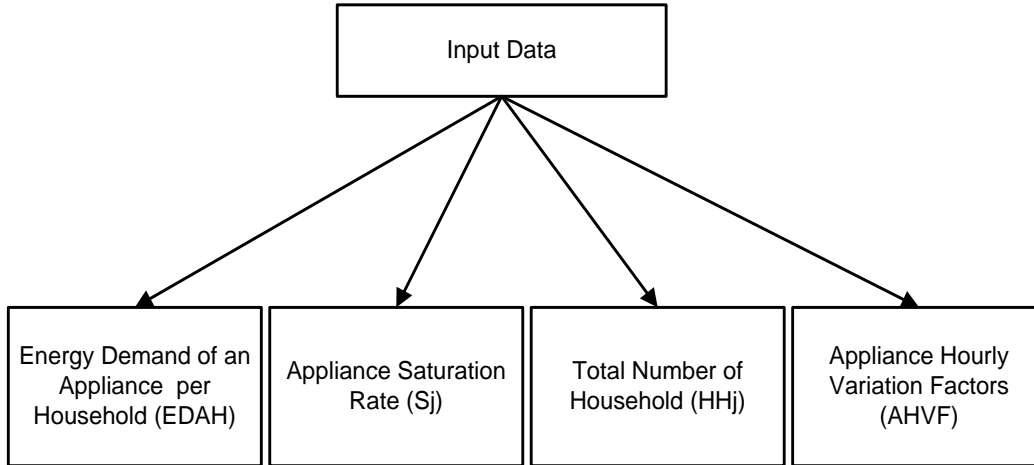
In the residential sector, proper understanding of consumer behaviour may be required for effective peak demand management. In fact, one of the main barriers to residential demand response is the lack of proper understanding of residential customer behaviour in responding to demand response requests [2]. There is a concern among demand response practitioners that demand response in the residential sector may simply move the peak problem with scale from one point in time to another. Load disaggregation or the behaviour of the different components of residential load will be required to study this problem, especially the effect of load shifting models on the aggregate load, but such disaggregated load data is usually not available.

In the first part of this paper, the diversified demand end-use model has been used to estimate the residential electricity demand profile for the city of Christchurch in winter, 2008. In this profile, the behaviour patterns of the different components of the residential load are represented, making it possible to study the effect of changes in appliance usage behaviour on the aggregate load curve. In the second part, three scenarios were developed through the use of an energy audit and stated preference survey to estimate the voluntary demand response (VDR) potential and its impact on the utility load curve. Finally, an economic evaluation is performed to estimate the economic value of the reduced load.

## **2. Appliance End-use model**

The appliance end-use model is a “bottom-up” approach of generating the aggregate load profile of residential customers in which the patterns of usage of individual appliances are represented. Appliance end-use models have been developed and successfully applied in electricity load forecasting and demand analysis. A Bottom-up approach has been used, for example, in the load model by Capasso et al. [3], where probability functions representing the relationship between the demand of a residential customer and the psychological and behavioural factors typical of households were established through the use of a Monte Carlo method. Paatero and Lund [4] also developed a simplified bottom-up model that is very similar to that of Capasso et al. but uses a representative data sample and statistical averages. The random nature of consumption was generated by using stochastic processes and probability distribution functions.

In this study, load curves of the major household appliances whose aggregate defines the load profile of residential customers were generated using the method of



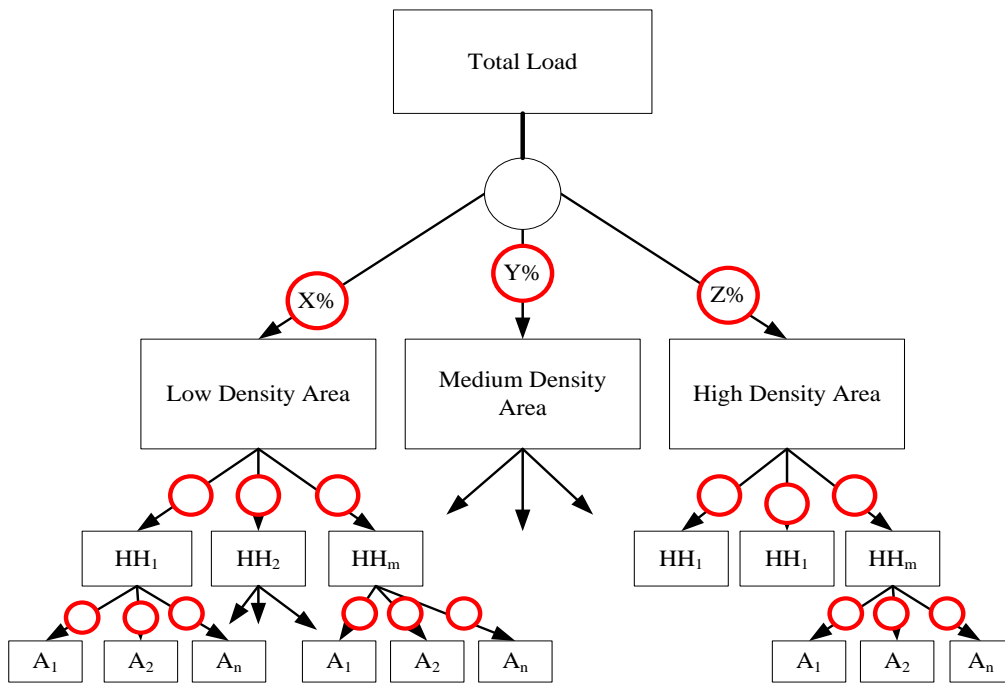
**Fig. 1.** A simplified diversified demand model input data

diversified demand. This method was developed by Arvidson in 1940 to estimate the load on distribution transformers when measurements of the actual load are limited [5]. The method of diversified demand has seen increased interest recently due to interest in residential demand response and the need for a component-by-component analysis of residential load.

According to the method of diversified demand, if a location can be considered, in aggregate, statistically representative of the residential customers as a whole, a load curve for the entire residential class of customers can be prepared. If the same technique is used for other classes of customers, similar load curves can be prepared [5]. The construction of the load curve requires certain load information to be available. Load saturation and load diversity data are needed for the class of customers whose load curve is to be generated. The method takes into account the fact that households may not be using all the electrical appliances that constitute the connected load of the house at the same time and/or to their full capacity. The curve is constructed from the most probable load. To obtain electricity demand for a group of households, the diversified demand per household is multiplied by the appliance saturation rate and then by the total number of households. The result is then multiplied by the appliance hourly variation factors. While the model is straightforward and conceptually simple, obtaining accurate and reliable input data remains a major obstacle. Fig. 1 shows the input data for the method of diversified demand.

### **3. Model Structure**

Fig. 2 illustrates the approach used to generate the load profile of the residential customers. The total system load is broken down into three load-density areas: low



**Fig. 2.** Illustration of the modelling approach for a group of customers

density, X%, medium density, Y%, and high density, Z%. Within each density area, the load is further broken down into the number of households,  $HH_i$ , and within each household, into a set of appliances,  $A_n$ . The appliance hourly variation factors provide the percentage of each load that is ‘on demand’ at each hour of the day. The red circles in fig. 2 illustrate the weighting factors as one moves down the model structure. For example, the bottom circles show the appliance saturation rates which indicate the percentage of households that own a particular appliance category (e.g. washing machine, freezer, dish washer, etc). The weighting factors for the different kinds of households are assumed to be uniform. X, Y and Z represent the percentage of the city that belong to low, medium and high density areas.

The maximum diversified demand (MDD) of an appliance category per household is given by the equation:

$$MDD_{(av, max)_i} = MDD_i * m * s_i \quad (1)$$

$MDD_{(av, max)_i}$  is the average maximum diversified demand of an appliance category for a group of customers (e.g. households in the low density area).  $MDD_i$  is the maximum diversified demand of an appliance per customer;  $m_i$  is the number of households.  $s_i$  represents the saturation rate of the appliance category and is defined as the percentage of households that own at least of one of the appliance of a given category.  $MDD$  depends on the total number  $n_i$  of appliance  $i$ . The  $MDD_i$  is a decreasing value as a function of the number of customers. In other words, peak load per customer drops as more customers are added to the group.

The  $MDD$  corresponding to different  $n$  for several household appliances is presented in Table 1 [5]. The hourly maximum diversified demand of an appliance



**Table 1.** Average maximum diversified demand per customers (in kW) for given number ( $n$ ) of different household appliances.

Appliances	n=1	n=5	n=10	n=20	n=40	n=80	n=100
Direct Water Heater	1.1	0.37	0.22	0.18	0.14	0.1	0.1
Heat Pump	4.50	3.00	3.00	2.60	2.60	2.60	2.60
Electric Heater	7.00	4.00	3.50	3.00	3.00	3.00	3.00
Cloth Dryer	4.30	1.80	1.50	1.20	1.200	1.20	1.20
Home Freezer	0.30	0.13	0.10	0.08	0.08	0.08	0.08
Refrigerator	0.18	0.07	0.06	0.05	0.05	0.05	0.05
Range	2.30	0.90	0.70	0.60	0.50	0.50	0.55
Lighting & Misc.	1.10	0.65	0.60	0.56	0.54	0.54	0.54

category applicable to a group of customers,  $MDD_{(t,max)i}$  is calculated from Equation 2.

$$MDD_{(t,max)i} = MDD_{(av,max)i} * f_i(t) = MDD_i * m * s_i * f_i(t) \quad (2)$$

Where  $f_i(t)$  is the hourly variation factors of the appliance categories. The hourly variation factors show what proportion of the different appliance categories are used by a group of customers over the course of the day.  $f_i(t)$  depends on the living habits of individuals in a particular area and may differ from location to location. These factors define the pattern of the load curves. The living habits in turn depend on the socio-economic characteristics of the population.  $f_i(t)$  can be obtained through load research. Gyamfi and Krumdieck have, for example, estimated winter hourly variation factors of some major household appliances for Christchurch [6]. Equation 3 derives the total group demand profile for the given period.

$$MLT(t, \max) = \sum_{i=1}^N MDD(t, \max)_i = \sum_{i=1}^N MDD_i * m * s_i * f_i(t) \quad (3)$$

Where  $MLT(t, \max)$  is the maximum load for the group of customers (e.g. low density customer group) at any hour of the day, and  $N$  is number of appliances categories ( i.e. washing machine, heat pump, clothes dryer, etc.).

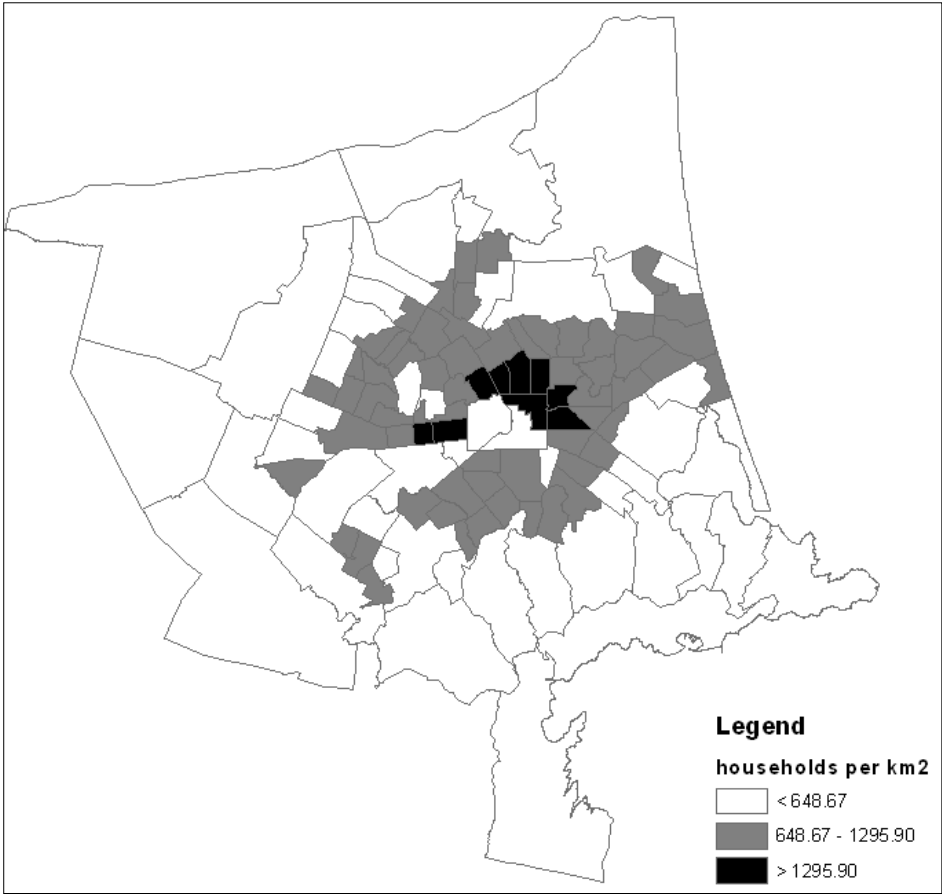
#### 4. Winter Load Profile of Christchurch City

The generic household appliance load curve methodology described above was applied to estimate the residential electricity demand profile for Christchurch city. The model input data were taken from previous studies. The number of households was taken from the Statistics New Zealand 2006 Census “Meshblock” dataset [7]. Table 2 shows the breakdown of Christchurch city into the three load density areas. Fig. 3 shows the spatial distribution of the load classes.

- Low density – area with less than 649 households per square kilometre;
- Medium density – area with between 649 and 1296 households per square kilometre;
- High density – areas with more than 1296 households per square kilometre.

The high and the medium density areas are concentrated around the centre of the city and are parts of the city where further development in terms of construction of new houses is limited. The housing density drops with distance as one moves out to the periphery of the city.

For each load density area, appliance saturation rates for New Zealand were used to calculate the total number of appliances in each appliance category in the area [1]. The saturation rate of heat pumps was taken from a recent BRANZ survey [8].



**Fig. 3.** Christchurch city map showing the three load density areas

**Table 2.** Detail characteristics of the three load density classifications in Christchurch.

<b>Classification</b>	<b>Households /km<sup>2</sup></b>	<b>Km<sup>2</sup> of land</b>	<b>% Size of the city</b>	<b>Total No. of Households</b>	<b>Average No. of households/ km<sup>2</sup></b>
Low Density	<649	427	83	43048	268
Medium Density	649 -1296	81	16	75596	945
High Density	>1296	9	2	14322	1592

According to the BRANZ study, New Zealand is experiencing a high up-take of heat pumps with about a quarter of households having heat pumps installed in 2008. In the Canterbury region where Christchurch is located, the number is even higher at 39% due to local government environmental law which limits the use of wood burners for space heating. In the future, heat pump saturation in Christchurch, and in fact in the whole New Zealand, is expected to increase further.

Given the large number of households, the maximum diversified demand per customer for each of the load density areas would be the same as the ones with the load of 100. It is through this demand data that any efficiency improvement scenarios can be incorporated into the model. The total maximum diversified demand for each appliance category for the group of customers is then calculated for each of the three load density areas. The maximum diversified demand per square kilometres for each of the load density areas was also calculated. Table 3 shows the calculated maximum diversified demand of Christchurch city. To obtain the load curves, the maximum diversified demand for each load density class was multiplied by the appliance

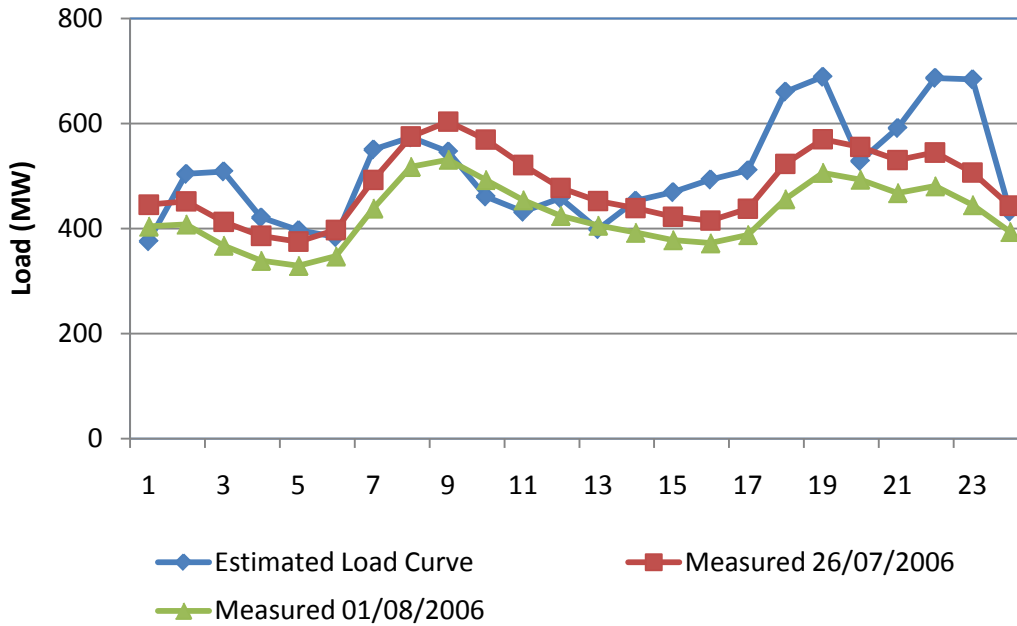
hourly variation factors of typical week day for Christchurch city developed by Gyamfi and Krumdieck [6].

**Table 3.** Calculated Maximum Diversified Demand (MDD) for the three load density areas of the city of Christchurch.

Appliances	Saturation (%)	MDD per Household	Maximum Diversified Demand					
			Low Density		Medium Density		High Density	
			kW	kW/km <sup>2</sup>	kW	kW/km <sup>2</sup>	kW	kW/km <sup>2</sup>
Domestic Water								
Heater (DWH)	0.87	0.72	31010	73	47353	585	8971	997
Heat Pump*	0.39	2.6	50198	118	76654	946	14523	1614
Electric Heater	0.93	3	138120	323	210913	2604	39959	4440
Clothes Dryer	0.7	1.2	41584	97	63501	784	12031	1337
Washing								
Machine	0.95	1.2	56436	132	86179	1064	16327	1814
Home Freezer	0.64	0.08	2535	6	3871	48	733	81
Refrigerator	0.31	0.05	844	2	1289	16	244	27
Fridge-Freezer	0.8	0.08	3168	7	4838	60	917	102
Microwave/Oven	0.78	0.5	19307	45	29482	364	5586	621
Range	0.93	0.55	25322	59	38667	477	7326	814
Lighting & Misc.	1	0.54	26733	63	40822	504	7734	859

### ***Reasonableness of Model***

To assess the reasonableness of the model, the estimated load profile was compared with the load measured by Orion Networks, the distribution company in the Christchurch area, in some selected weekdays in winter 2006, when the demand for electricity was high. Fig.4 shows this comparison. The shape of the estimated load curve compares very well with the load profile measured by the utility



**Fig. 4.** Comparison of the estimated and the measured load in some selected days in winter 2006 when electricity demand was high

company. The shape of the load profile measured by the utility company remains largely the same. The magnitude of the curve may vary greatly from day to day, mainly due to weather affecting the heating load.

## **5. Demand Response of Residential Customers**

Demand response can simply be defined as consumer actions that can change any part of the load profile of a utility or region [9]. Demand response can be used to ensure supply-demand balance during supply or distribution constraint situations. As countries aspire to generate a large amount of their electricity from renewable resources, scheduling enough generation to meet demand during peak hours is going to be a challenge. Demand-supply balance can be achieved in such situations by increasing the existing capacities for energy storage and by adapting significant shares of the electricity demand to the available renewable energy production. Influencing the energy demand at short notice will be an instrumental in dealing with this challenge in the future.

Until now, demand response has been focused on the large industrial and commercial sectors. For the residential sector, information and communication requirements and assessment methods are not well understood and/or developed [10]. This section reports a methodology developed to estimate voluntary demand response of residential customers. Three scenarios: *demand reduction*, *demand shifting*, and *combination of demand shifting and reduction* are then developed to assess the potential of residential demand response in Christchurch.

A key success factor to achieve demand response in the residential sector is to understand customer behaviour and the willingness to participate in a demand response program. All technical appliance demand reduction and shifting potentials

will be irrelevant if householders are not in support of programs to achieve demand reduction. It is also important to note that residential consumers might not be “smart” enough even if they have smart appliances.

For this purpose, a residential demand response survey was conducted in Christchurch city in the winter of 2008. The aim of the survey was to develop a picture of representative household electricity usage behaviour during peak times in Christchurch. This energy usage behaviour has two components, the activities being carried out and the appliances that are being used. The other aim of the survey was to determine customer stated preferences for demand response in two ways:

***Activity response*** – households change normal activity pattern by shifting activities from the peak periods.

***Mode response*** – households maintain normal activity pattern but reduce energy demand by turning off un-needed appliances or changing energy intensity.

The survey was conducted in the winter month of June, 2008. The questionnaires were placed in envelopes addressed to the individual houses along with a reply envelope affixed with a stamp. The envelopes were hand-delivered to mailboxes of randomly selected households in Christchurch. All the selected households together give a general idea of the characteristics of houses in Christchurch.

The survey included a detailed cover letter that explained the reason for the research and a consent form. The cover letter stated the aim of the project which was “to develop innovations for electricity supply security”. The front page of the survey contained an explanation of peak demand and the relationship between peak load and the cost of electricity, environmental impacts and supply security. The front page of the questionnaire contained information on load curves of the utility on the day of a global warming public campaign in New Zealand called *Earth Hour*, showing the



effect of the voluntary customer energy use reduction on the load curve. *Earth Hour* is a global sustainability movement that started in 2007, where people voluntarily switch off electrical appliances as a pledge of support to our planet during a designated hour [11]. This event took place several months before the survey and was well publicized in Christchurch.

The survey included an energy audit section which was structured to gather data about how electricity is used in the households. Participants were asked how they use electricity to carry out their normal daily activities during winter morning and evening peak hours. This was done by supplying a list of the usual appliances, organized by activity that participants could tick and then circle a number representing the frequency of this activity (1 = seldom, 2 = sometimes, 3 = always). A scenario was then set out whereby supply constraints or emergency required allocation of a certain amount of power for each household during the peak hours, and the amount was less than what is required for normal use. Participants were asked about the appliances they would switch off or avoid using. A monitoring experiment in which the behaviour of households is observed under realistic future conditions would give more accurate results, but such experiments are expensive to conduct and are not practical within this time frame of the project.

### ***Survey Results and Analysis***

A total of 78 out of the 400 surveys distributed were completed and returned by participants. No follow up survey was done. The participant's responses to the level of usage of each appliance was converted into a single factor by applying the following weighting factors to the three levels: seldom:  $w_1 = 1$ , sometimes:  $w_2 = 2$

and always:  $w_3 = 3$ . The probability factor,  $P_i$ , was referred to as the likelihood of appliance usage at peak hours. This factor is defined in equation 4.

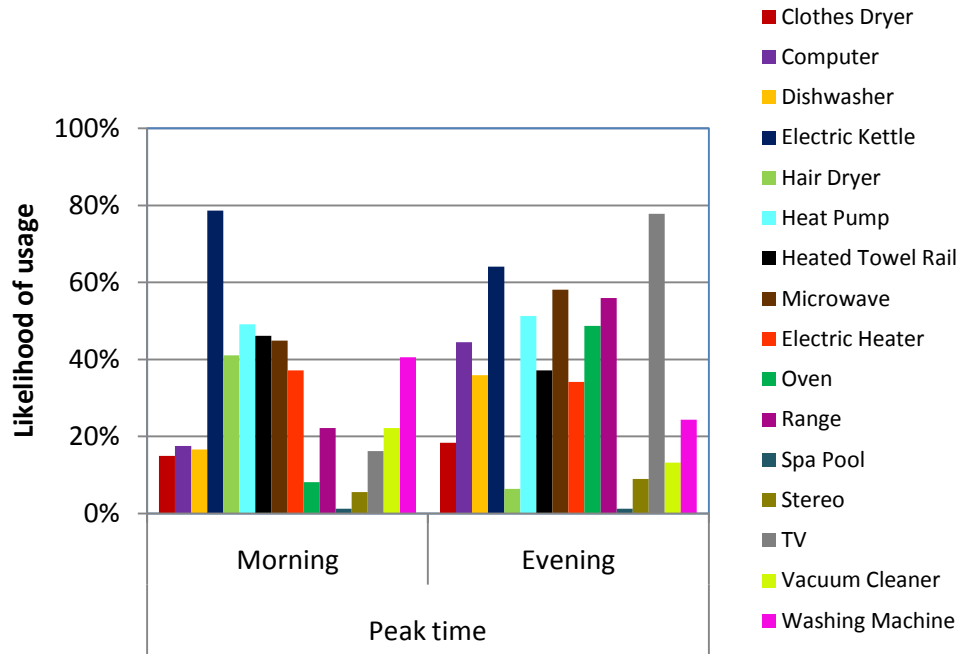
$$P_i = \frac{n_{i1} \times w_1 + n_{i2} \times w_2 + n_{i3} \times w_3}{n \times w_3} \quad (4)$$

where  $n_{i1}$ ,  $n_{i2}$ , and  $n_{i3}$  are the number of customers indicating the use of an appliance, as “seldom”, “sometimes”, and “always” respectively, and  $w_1$ ,  $w_2$ , and  $w_3$  are the respective weights assigned to the levels.  $n$  represents the total number of households that responded to survey (i.e.  $n=78$ ). This factor represents the probability that a particular appliance will be used, out of the pool of possible appliances during the peak times. Fig. 5 shows the likelihood of appliance usage during peak hours.

To get an idea of achievable appliance demand response potential, the likelihood that an appliance will be used during peak hours was combined with the likelihood that the usage of that same appliance would be altered during peak hours. The achievable demand response participation is defined as the product of the likelihood that an appliance will be used during peak hours and the likelihood that the usage of that same appliance would be altered by customers during peak hours.

The following scenarios were developed to estimate the potential maximum demand reduction if customers would modify their behaviour according to their stated intentions in the survey.

**Scenario 1: Demand reduction** – in this scenario, customers’ co-occurrence demand reduction through modification of the usage of heat pump, electric heater, microwave and range (electric stove) was calculated.



**Fig. 5.** Likelihood of appliance usage at the morning and evening peak hours

**Scenario 2: Demand Shifting** – in this scenario, customers’ co-incident demand shifting of two major flexible appliances: clothes dryer and washing machine was calculated.

**Scenario 3: Load reduction plus load shifting** – if customer intended demand reduction and demand shifting activities coincide during the morning and evening peak hours. Table 4 shows the demand response characteristic of each of the three scenarios.

**Table 4. Achievable demand response potential for Christchurch obtained through demand response survey.**

Appliances	Peak Usage		DR Potential indicated by		Achievable DR	
	Likelihood (%)		Participants (%)		Participation (%)	
	Morning	Evening	Morning	Evening	Morning	Evening
<b>Scenario 1: Demand reduction</b>						
Heat Pump	49	51	26	21	13	11
Microwave	45	58	24	19	11	11
Electric Heater	37	34	32	32	12	11
Range	22	56	27	23	6	13
<b>Scenario 2: Demand Shifting</b>						
Cloth Dryer	10	15	44	41	4	6
Washing Machine	41	26	62	52	26	14

For each of these scenarios, customer peak demand reduction was calculated from equation 5.

$$ADR_{i(t)} = MDD_i(t) * dx_i \quad (5)$$

Under scenario 1, morning and evening peaks reduction of 8.0% and 6.3% were achieved respectively. In the second scenario where the shifting of clothes dryer and washing machine were considered, 3.7% reduction in morning peak load and 2.7% reduction in evening peak load were achieved. Finally, an average of 11.7% and 9.0% reduction in morning and evening peak load respectively was achieved by combining scenarios 1 and 2. Fig. 6 shows impact of each of the three scenarios on the peak load.

The results show a great potential for the reduction of morning and evening peak load on the utility network through residential demand response. To realize this potential, residential customers would need to be provided with enhanced supply constraint information followed by an appeal to reduce demand during peak periods. Customers should be made aware of the advantages of being a “smart” consumer or having smart appliances. All the benefits, apart from financial aspects, like CO<sub>2</sub> reduction, supply security and transparency of consumption could be communicated to the consumers. Broadening the scope of information conveyed to customers would enhance customers response [6]. For demand response to be successful in the residential sector, strategies need to be developed to address the constraints that limit the acceptance of the demand response concept by the different actors (appliance manufacturer, producer of domestic energy supply systems, electric utility companies, policy makers, and consumers) [10]. For example, the washer and dryer may be operated in continuous mode where drying automatically follows a washing cycle. By using a timer function, laundry can be shifted to start at night and finish in the morning before many of the other morning household activities start. Appliance manufacturers can develop appliances with timer capabilities to facilitate residential demand response. This can be critical to realizing the demand response potential of

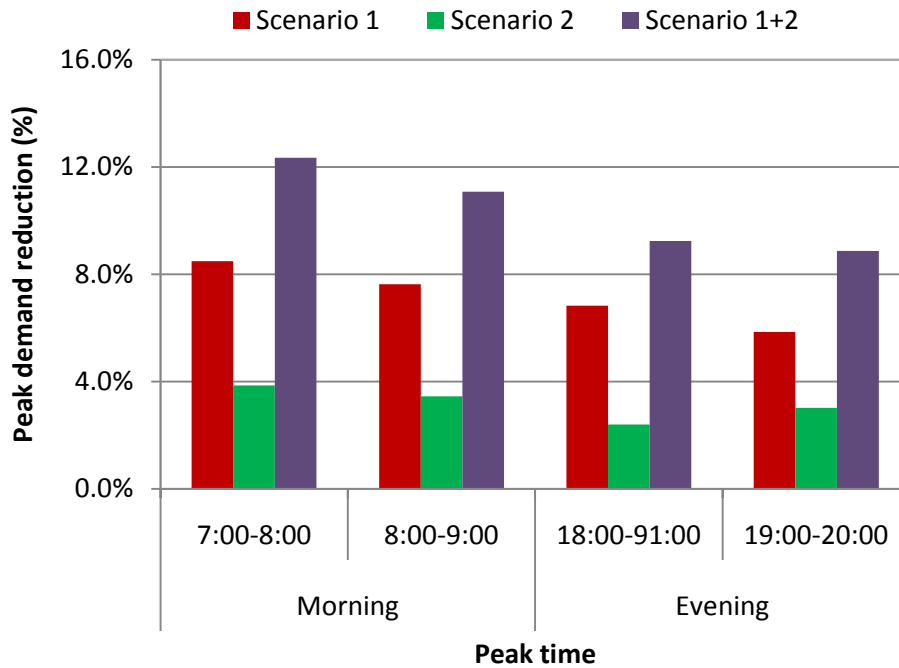


Fig.6. Peak demand reduction under each of the three scenarios

the residential customers in Christchurch and New Zealand as a whole, even though the realization of such demand response technology may require a longer time to be realized in New Zealand.

## **6. Economic Value of Demand Response**

The value of VDR in Christchurch was estimated based on the avoided cost methodology. This method considers demand response as an alternative source of electricity generation capacity. The cost effectiveness of demand response is estimated by comparing the benefit in terms of avoided investments, which would otherwise have been required to supply the load, to the investment costs required to secure the load reduction. It is a more conservative estimate and excludes benefits that are not easy to quantify, such as environmental benefits, societal cost, risks and the market effect of a reduced peak load.

The main problem of supplying peak load in Christchurch is related to transmission and distribution bottlenecks and hence only these two components were taken into account when estimating the cost effectiveness of the VDR. We assume there is enough generation capacity but limited transmission capacity. The distribution company in Christchurch estimates demand response value based on avoided new network capacity addition. This value is calculated based on the so-called Long Run Average Incremental Cost (LRAIC) of the new transmission capacity of around NZD \$50/kW and distribution LRAIC which is reported to be NZD \$100/kVA per annum [12]. By using these values, the average of the morning and evening VDR value of

about 65.75 MW would correspond to about NZD 3.28 million of avoided transmission cost and NZD 6.57<sup>1</sup> million of distribution cost per annum.

### *Cost effectiveness of VDR*

The cost effectiveness of VDR was estimated by simply comparing the avoided investment cost to the cost of investing in advanced metering infrastructure that would make it possible to secure the demand response benefits. Estimating the cost of potential demand response programs has received far less analysis in the literature compared to the benefits, the reason being that the cost can vary widely from one utility to another and any attempt to develop a general cost estimate may leave out important differentiating cost drivers. Table 5 shows recent capital cost estimated by three different demand response research groups in the US [13]. The average of these values was assumed for this study.

**Table 5.** Capital cost of advanced metering infrastructure for residential customers

Source	Costs per customer in		Costs per customer in	
	US\$		NZ\$	
	Low	High	Low	High
KEMA (2009)	100	450	120	542
EPRI (2011)	70	140	84	169
SGIG	200	400	241	482
Average	123	330	149	398

The cost per kW of the reduced peak load was calculated by making the following assumptions:

<sup>1</sup> Assuming a power factor (PF) of approximately 1. PF = kW/kVA



- Average demand response program costs per customer of NZD 149 and 398 under low and high costs scenarios respectively.
- Average peak hour demand reduction of 65.75 MW (average of the morning and evening peak demand reduction on a hypothetical supply constraint situation).
- The demand reduction is persistent over 10 years.
- Total number of 132, 966 households in Christchurch
- Assumed discount rate of 5%.

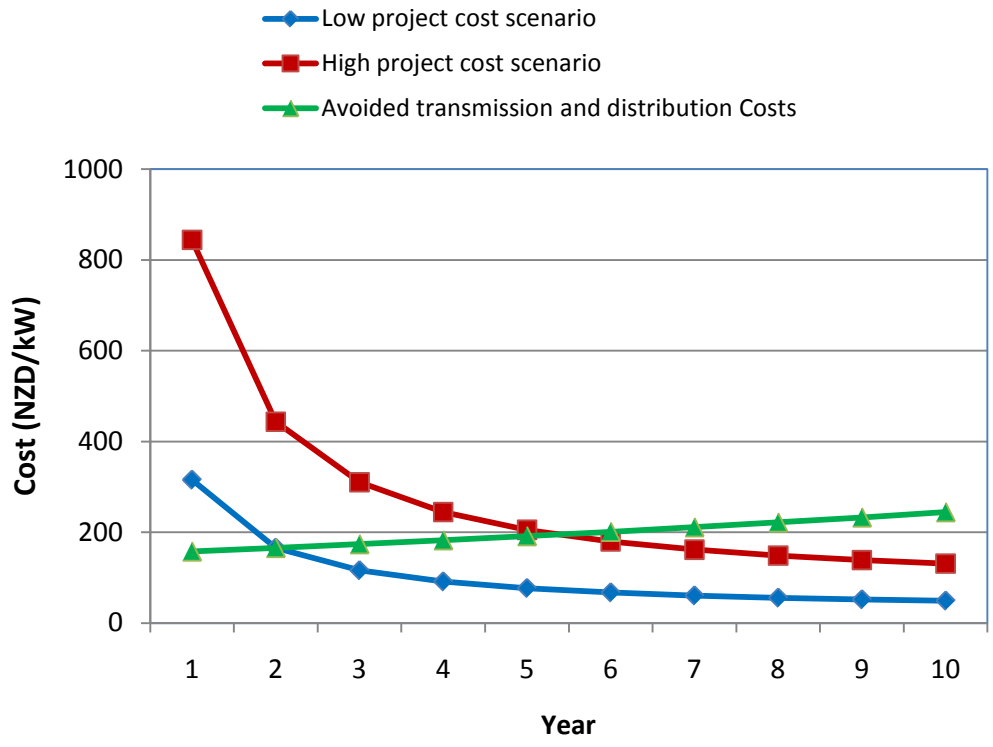
The future value of the cost per kW ( $FC$ ) at any particular year  $n$  was calculated from Equation 6.

$$FC_n = \frac{PC(1+r)^n}{\sum_{n=1}^n DR} \quad (6)$$

$FC$  is the cost per kW (NZD/kW) of the reduced peak load,  $PC$  is the project's total present cost (in NZD),  $n$  is the number of years,  $r$  is the discount rate and  $DR$  is the reduced demand (kW). Fig. 7 compares the investment cost of the demand response program against the avoided investment cost. Under the low cost scenario, the program pays for itself after 2 years and then begins providing positive returns while under the high cost scenario, it pays for itself after 5 years.

## 7. Conclusions

Residential demand response programs have great potential to provide cost benefits and improved network supply security. Electricity demand data for the different components of residential load over the period of the day is necessary for modelling and for developing demand response programs. This kind of information is not being provided by the utility companies. Lack of proper understanding of customer



**Fig.7.** Cost-benefit analysis of VDR in Christchurch, New Zealand.

behaviour concerning the usage of different household appliances is another issue for residential demand response assessment. This paper has shed some light on how demand response assessment could be done in the residential sector even without measured data. The diversified demand method allows further analysis of the effectiveness of individual household appliances in reducing the peak load on utility network. The diversified demand method and residential demand response survey were used to estimate the potential demand response in Christchurch, New Zealand. The results showed that a total of up to 11.7% reduction in the morning peak load and 9% of the evening peak load was possible. Assessment of the cost effectiveness of the VDR program shows that the project could pay for itself after four years.

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