Price, Environment and Security: Multi-Modal Motivation in Residential Demand Response

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Peak demand has been a growing problem for both security of supply and cost of generation and transmission. International research has attributed a significant influence of human behaviour on home energy for homes with similar households and appliances. Demand side management has had many successful programmes aimed at managing demand growth and load shape. The energy management strategy, "Demand Response", aims to achieve peak energy demand reduction by eliciting behaviour change. Demand Response management encompasses energy needs analysis, information provision to customers, behaviour induction, smart meter technology, and new signalling and feedback concepts for residential customers. There is concern that pricing mechanisms alone may impact negatively on lower-socio economic households. This paper reviews the two main strategies that have been used to reduce residential demand for electricity at peak times, direct load control and variable pricing. The current research program studies residential energy activities during winter morning and evening peaks and possible behaviour modifications to manage peak demand. This paper reports the demand response to three different signals: price, environmental impact, and risk of black-outs. The results show that demand response could effectively be achieved by focusing on normal energy use activities at peak times and the behaviour of the members of households during peak hours. A programme to develop the necessary technology and provide credible information and understandable signals about risks and consequences could reliably provide up to 30% temporary residential demand reduction at critical times. In this study, householders are informed about the relationship between the three factors and peak demand. Demand response is analysed as multi-mode motivation and responsiveness from stated preference surveys of customer energy use behaviour change. The survey results for Christchurch show that response to security signals is on par with price signals, environmental signals produce a strong response, and that all households respond to at least one of the signals.

Keywords: *Demand Response, Behaviour Motivation, Household Energy Use, Residential Energy Consumption*

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1. Introduction

The residential sector uses about 33% of electricity produced in New Zealand and accounts for the largest share of the growing peak demand and the related emissions into the environment. Activities such as space heating, water heating, lighting, refrigeration and the use of other major appliances account for the electricity consumption in this sector [1]. The growing peak demand coupled with a decreased margin of the installed capacity over peak load has necessitated the need to build new gas fired power plants [2, 3]. This has a contributing factor in retail electricity unit price inflation. An alternative to expanding infrastructure to meet the increasing peak demand is to focus on managing that demand. Demand Response can broadly be defined as electricity consumers responding to external indicators by changing their normal grid-electricity usage patterns [4]. Research shows that occupant behaviour has a very large impact on residential energy use [5, 6]. Indeed, the famous paper by Socolow demonstrated that behavioural influences are much larger than the impact of intrinsic differences in building materials and energy consuming appliances. Demand Response is a type of Demand Side Management strategy aimed at short-term behaviour changes to maintain the safe margin between generation and/or distribution capacity. A secondary goal of Demand Response programmes is to reduce inflation of electricity unit price.

Two basic strategies have been used in America and Europe to control residential peak load: *time-of-use pricing* and *direct load control*. The time-of-use demand response approach relies on a clear pricing signal, usually communicated via the monthly power bill. Price differentials an order of magnitude higher at peak times are needed in order to influence customers to shift their electricity usage from peak to off-peak hours. The most common residential pricing signal is a fixed tariff structure with higher unit prices during the usual peak periods. Customer response in this case is driven by an internal economic decision-making process, and the load modifications are entirely voluntary. Residential customers have rarely been subject to a spot market price. However, these types of tariffs have been criticized for equity reasons as households who do not own large energy consuming appliances like a heat pump do not qualify to benefit from the programme. Also, the levels of price that may be required to achieve the needed response can be higher than what is affordable to lower socio-economic households [7].

Direct load control, unlike the time-of-use pricing approach, offers households cost incentives in exchange for the utility interruption of some large energy consuming household appliances. Air conditioners are commonly ripple controlled during summer peak air conditioning demand in the USA and Europe. Ripple control of water heating cylinders is a direct load control program on some networks in New Zealand. It has been very successful in managing residential peak demand in Christchurch [8]. However, the supply interruption is seldom communicated to customers, and depending on their hot water usage patterns, Christchurch residents have experience "cold showers" as a result.

In this paper, reduction of residential peak demand through voluntary demand response participation is explored. The relationships are explored between peak demand and three important factors: cost (price), environment (CO_2) and security (blackouts) to persuade household consumers to change their peak-electricity usage behaviour. The research reported in this paper is the first step in a project to develop novel smart, informative, and feedback-enabled metering technology. Information, socialisation and feedback are necessary in order to influence human behaviour [7]. The facts about network operation, generation, and costs of peak supply would represent the information component. Real-time connection to generation status, current price and CO_2 emissions would represent the socialisation component. A signal for load reduction due to exceeding system conditions of pre-set capacity margin, price or CO_2 limits would be given via the new "smart" meter interface, and feedback about collective response and system condition would be given. This integrated behaviour modification design is a new approach, requiring research in multi-mode demand response elasticities.

A survey of residences was done in Christchurch to determine customer willingness to adjust their normal winter morning and/or evening activities in response to each of the three factors; price, environmental impacts and supply security. This survey focused on the information and socialisation aspects of the larger research and development programme. Customers stated appliance use modification preferences at peak times will be used to determine the maximum possible residential demand reduction. The power reduction resulting from stated activity change as a function of the strength of the signal is the demand response elasticity. Household response and motivation with respect to each factor are reported. The results show that by broadening the scope of information conveyed to the residential customers the system-wide demand response could be substantially greater than for the price signal alone.

2. Demand response experience in the residential sector

Historically, utilities have used two strategies to reduce residential peak load: direct load control programs and variable pricing tariffs. Direct load control programs are typically mass-market programs directed at residential customers. A customer agrees to allow the utility to control the mode of operation of a specific electrical appliance and receives a price incentive. The most frequently controlled residential end-use appliances are central air conditioners, water heating cylinders, electric space heaters with storage features, and non-essential lighting. The use of direct load control differs between geographical areas and depends on the load pattern of the location. In Southern Australia, direct load control is used to control summer air conditioners [9]. In New Zealand, direct control is used to control hot water heating cylinders in the winter. In Christchurch for instance, the network company Orion is able to manage residential load ranging from 125 – 150 MW by the use of ripple control [8]. Orion requires all new residential water heating cylinders on the network to be ripple controlled because of constraints on network capacity [10]. Despite its effectiveness, direct load control programs have been criticized for the following reason: they offer fixed financial incentives for unmeasured load. For example, the bill credit given by the utility is the same regardless of the amount of load reduction accessed by the utility. In Orion's case, the benefit is linked to the 'economy rate'. All customers on the 'economy rate' receive the same credit on their monthly electricity bill [11].

The other residential peak demand reduction program is time variable pricing. This category employs different pricing mechanisms including Time-of-Use Pricing, Critical-Peak Pricing, and Real-Time Pricing. Based on the theory of utility maximization and consumer rationality, the proponents of the pricing concept assume that individuals seek to maximize utility given a budget constraint. A decision outcome with higher utility will be consistently preferred to an alternative outcome with lower utility [12, 13]. Instead of directly controlling customer load at peak times, the pricing mechanism aims at influencing customers to shift the usage of electricity from peak to off-peak hours by charging a high price per unit of electricity consumed during peak hours. Consumers receive relevant price signals as the unit cost reflects the actual cost of electricity at the time it was provided.

However, there is a wealth of experimental and field evidence that individuals do not make consistently rational decisions [14]. This is explained by the fact that most people are only partly rational, and in fact emotional or irrational in the remaining part of their actions. People's energy-saving decisions are therefore said to be best characterized by the concept of 'bounded rationality' [13] where one bound assumes the rational behaviour and the other bound assumes individual decisions to be subject to constraints on their habits, intentions, resources and ability to process information. This theory has been used to explain the energy efficiency gap that is repeatedly identified in economic-engineering studies. The potential reduction in energy demand from the adoption of more efficient technology has remained underutilized despite significant lifetime saving and attractive payback time. This theory may also be used in demand response to explain peak demand price unresponsiveness. Of course, in the case of residential energy consumers, the activities taking place during peak times may not be rationally curtailed or delayed in order to avoid a small marginal cost increase. We would not expect people to leave dinner half cooked, to endure a cold home if health is at risk, or switch to candles.

Time varying pricing is employed in New Zealand for large industrial and commercial users with special half-hour interval metering that records customer demand during peak times. This type of pricing is currently not available for the residential customers. The residential sector enjoys a flat or split rate for electricity consumption. They can, however, decide between night and day-time rates or put some heating appliances on night rate. Even if people would make economically "rational" decisions and reduce the use of electricity at peak times, one issue still remains – impact of price on lower-socio economic households. These households use less electricity than the average consumer, and as a result, their ability to conserve is lower [15]. Also, when confronted with an increase in energy costs, lower-income families tend to make "lifestyle cutbacks"[16]. Therefore using a pricing mechanism to achieve demand response will not be consistent with all the principles of rate design such as the promotion of social equity and affordability to low income households [17].

3. Multi-modal demand response motivation

The limitations of price and direct load control mechanisms provide an opportunity to explore other ways to achieve effective demand response in the residential sector. Energy demand is influenced by external factors that may also stimulate individuals or householders to take on energy saving measures. These external factors include not only increased price but also water or fuel shortages, energy crisis and environmental concerns. This study explores the customer response to three external factors: cost (price), environment (CO_2) and security (blackout). The potential impact of each of these factors as a customer peak reduction motivator is determined through a household survey in Christchurch. The elasticity of demand with respect to price, environment and security is determined through the survey. This paper describes the first results from a larger trial. In-depth analysis of the residential peak electricity demand is being carried out by developing an activity system model calibrated to the residential sector in Christchurch by using the survey data. The responsiveness to motivational factors will be used to calculate electricity demand reduction, and to inform concepts for new communication technologies that could be used to manage residential peak demand.

3.1 The Motivation factors and the user in past studies

The potential of using price as a feedback on energy consumption to reduce demand has been well emphasized in many studies. The analysis of residential customer response to price has involved estimating the magnitude of customer load change and calculating the value of elasticity parameters that characterize the degree of price responsiveness. There have been some large and small scale experiments to study the impacts of high prices on electricity demand during peak hours. One of the large scale experiments conducted in the residential sector is the California State-Wide Pricing Pilot conducted to test the impact of several pricing structures on peak demand [18]. A total of 2,500 customers were involved in the experiments that ran from July 2003 to December 2004. This experiment found average demand reduction of 13% for low-demand customers (mainly residential customers with demand less than 20 kW). The estimated price elasticity (kW change per unit price change) of substitution varied from -0.04 to -0.13 for peak to off-peak price ratio of 3 to 6 [18]. Another experiment conducted in Canada by Ontario Hydro found overall saving of 13% across the 25 homes that were involved [19]. A review of past studies drawn from North America found price elasticities between -0.12 to -0.35 [20]. Note that negative elasticity means a demand reduction in response to a price increase.

There is a direct relationship between peak demand and environmental emissions. This relationship depends on the generation mix and how they are dispatched to the market [21]. While adverse environmental impact of energy production and use have been used by environmentalists in many energy conservation campaigns, we have not come across a demand response study that uses the emissions to the environment at peak times as a signal to persuade consumers to reduce demand. In New Zealand, peak demand is the underlying reason for new gas generation, but on a daily basis, the peak demand is met by peaking hydro. However, in Christchurch, there are about 90 diesel generators owned by the city council and other institutions that are used to meet demand during peak hours [22]. This is due to the transmission constraint into the city. If residential customers in Christchurch could reduce their demand at peak times, the use of these diesel generators during peak demand hours would be reduced and hence a direct reduction in CO_2 emissions and local air pollution would be achieved. If peak demand in the country as a whole were to be managed so as to limit growth, the need for gas and coal generation could be reduced.

Security of electricity supply refers to the ability of the power system to provide electricity to end-users with a specified level of interruption and quality in a sustainable manner, relating to the existing standards and contractual agreements at the points of delivery [23]. It is the responsibility of the different sectors of the industry to ensure supply security. There is a direct relationship between peak demand and supply security. This is often expressed in terms of Loss of Load Probability (LOLP). This LOLP is higher at peak demand hours than at off-peak hours. Linking residential behaviour to social consequences, such as rolling blackouts that could endanger the health and safety of some people, can provide extra impetus to the peak demand reduction. In New Zealand, low precipitation levels or maintenance on large generation units can cause supply security issues. Examples of other places where the security factor has been used to achieve demand reduction include France, during the 2003 heat waves [24], and in California during the state's 2001 energy crisis [25]. Table 1 shows the most important motivating factors for conserving energy given by respondents a survey that was conducted after the energy conservation campaign in California in 2001.

Motivation for reducing demand	**Respondents (%)**
Very important to stop energy suppliers from overcharging	79%
Using energy resources wisely	78%
Keeping bills down	77%
Trying to avoid blackouts	77%
Doing our part	69%
Qualify for utility rebate	33%

TABLE 1: Motivations quoted as important by participants during the "Flex Your Power" Energy Conservation Campaign in California after 2001 energy crisis

4. Study method

In this study, a survey was conducted to determine how household energy use behaviour could be influenced by three factors: price, environmental impact, and security. Energy use behaviour is a factor of two components: the activities being carried out and the appliances being used. The survey collected data to correlate network demand reduction with particular behaviour changes: curtail or shift activities, conserve by turning off un-needed appliances. Stated behaviour change preference is used to estimate the possible peak demand reduction. The survey questions were divided into two main sections: household information and stated preferences for saving electricity at peak times.

This paper reports one survey conducted in Halswell, a suburb of Christchurch. This area is unique, in that it has its own residential power feeder. This feeder was selected in consultation with Orion Networks, a power distribution company in Christchurch so that the real power consumption data could be used in future modelling. The homes in the Halswell suburb were all built between 15-8 years ago, so are relatively new and all in the same condition. All homes are insulated and heated with electricity. All water heating is supplied by electricity, and roughly half of the residences in the suburb have water cylinders on ripple control. Figure 1 shows the average power demand on the Halswell feeder for week days, Saturday and Sunday in July 2006. The morning and evening activity peaks are evident, as is the ripple control load reduction at 6:00pm. The high peak in the middle of the night represents the network control of all water cylinders and nightstore heaters. The high residential load at night is not a problem for the network as commercial and light industrial loads are not present.

The survey was placed in an envelope addressed to "resident" along with a stamped return envelope, and hand delivered to every mailbox in the Halswell subdivision. In total just over 400 residential customers are on the Halswell electricity feeder. The respondents were offered the chance to be in a draw to win one of 10 Centameters^{TM} if they returned the survey and selected a box to be in the draw. A Centameter is a real-time power monitor with display unit in the house valued at \$140. The

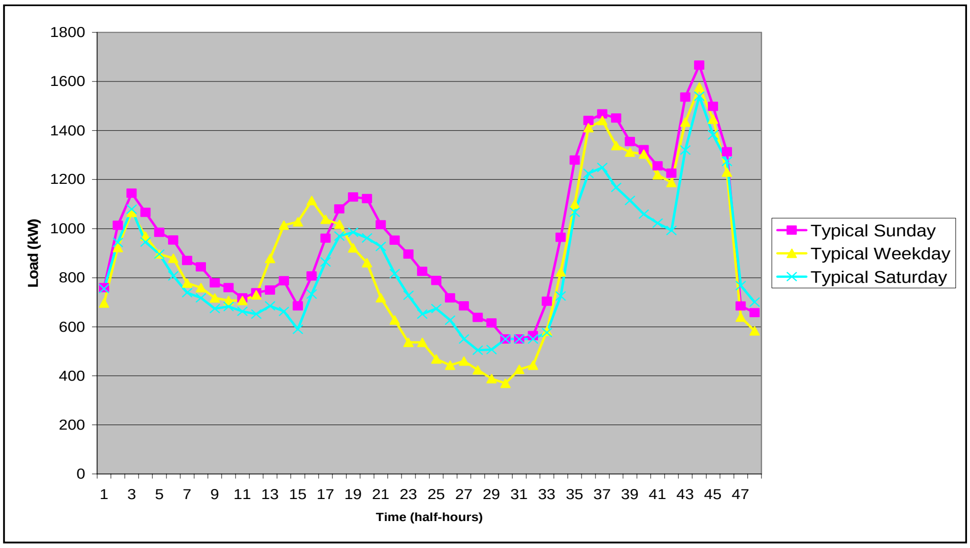

FIGURE 1: Average electricity demand for the 400 residents in the Halswell suburb during the winter month of July 2006. The last peak represents network controlled water heating loads. Time is quoted in 30 minutes intervals from midnight

household response rate was 16.3% with one survey returned without completing. The number of completed surveys was statistically significant sample for the number of households. No follow-up reminder or prompt was carried out after the initial mailbox drop. The respondents' personal information indicated a good demographic correlation with the general Christchurch population.

The survey included a cover letter that explained the research purpose and details of ethics approval and confidentiality. There was also a plot of the Christchurch power demand on the day of the Earth Hour event in order to illustrate the concept of demand response. A short explanation was given in the cover letter about the high cost of producing peak power, the higher CO_2 emissions in Christchurch if diesel generators were needed, and the risks of power outage if demand exceeds the supply capacity of the grid.

4.1 Demand response survey structure

To understand how electricity is used in households, we asked participants to tell us about how they use power to carry out their normal daily activities during winter morning and evening peak hours. Lists of typical appliances associated with kitchen/dining, bedroom, bathroom and lounge were provided with room to insert other appliances. Participants were asked to fill in the number of appliances they have, and to indicate whether it would be in use during the morning and/or evening hours. The reported appliance loading and activity-related appliance use were used to develop a model of the electricity demand for the 400 household feeder. Nominal power consumption rates for appliances and standard appliance penetration probabilities were used to develop a load model which was further adjusted to fit the actual residential feeder data. This represents the "no response" power load.

As a control, we asked participants about the appliances they would switch off in a scenario where they are allocated a limited amount of power, less than what is required to carry out their normal household activities, due to an emergency situation. By using the nominal electricity demand capacities of the appliances, the total possible demand reduction during peak hours was calculated from customers' stated preferences in reducing demand during an unspecified emergency situation. This restricted, yet voluntary demand response for the morning peak represented 40.9% of 1 July 2006 morning peak load while that of the evening of the same day represented 28.8% of the evening peak load. In the scenario it was explained that the load or activity could be postponed and resumed after the peak period.

The importance of price, environment and security as household participants' electricity demand reduction motivation factors were explored through the final section of the survey. Customers were first asked to rank each of the motivating factors on a scale of 1 (lowest) to 5 (highest) in terms of how they would be influenced by each of the factors. The three factors were then explored separately. Participants were first asked what they would consider to be a "high" price rise, then asked how they would modify their power consumption if the price during peak times went up to that high price. Next, participants were asked to give a range of power generation from non-renewable fuels that they considered to be "high". Again they were asked what they would modify if the carbon emissions during peak times became high due to fossil fuel use. Finally, participants were asked how many power disruptions in the form of brown-outs or black-outs they considered to be “high” over the course of a year. They were then asked to indicate demand reduction measures they would take if the risk of power disruption was high.

4.2 Analysis

The first question about relative importance of the three factors was analysed by plotting the responses and then calculating a weighting factor from the data. The total score of each of the factors was determined from the equation:

$$\mathrm{W_f} = \sum_{j=1}^{n} w_{fj} \tag{1}$$

Where $\mathrm{W_f}$ represents the numerical importance of the factor f and w_f is the score given by the j^{th} customer to that factor.

Elasticity is commonly used in economic analysis. Elasticity refers to a measure of the responsiveness in the quantity demanded to changes in the price. In this analysis we are interested in the responsiveness to the factor. In future work the electricity load modelling will be used to calculate electricity demand reduction from survey responses. The factor responsiveness for this survey was calculated as the ratio of the cumulative percentage of participants responding to an associated change in each of the factors. The price change is expressed as percent increase from current unit price during the peak period. The environmental impact factor was expressed as a total percentage of non-renewable generation rather than as a change from a non-peak condition. This was done because many South Island residential customers perceive that their power supply is provided by hydroelectricity alone. The security of supply factor was expressed as a total number of power supply disruptions in a year. As there have not been any blackouts in Christchurch for several years, even one event represents a 100% change from current status. Thus, the calculation of responsiveness, $\mathrm{R_f}$, to each factor is calculated from the following three equations:

$$\mathrm{R_{price}} = \text{(Cumulative Participant Response)} \div \text{(\% Price Increase)}$$

$$\mathrm{R_{environment}} = \text{(Cumulative Participant Response)} \div \text{(\% Non-Renewable Generation)}$$

$$\mathrm{R_{security}} = \text{(Cumulative Participant Response)} \div \text{(Number of Power Supply Disruptions)}$$

As mentioned earlier, this paper provides the first results that show responsiveness to

5. Results

Figure 2 shows the direct response from the participants in response to the question:

> *How important are each of the three following factors in relation to how you might change your power use during peak times?*

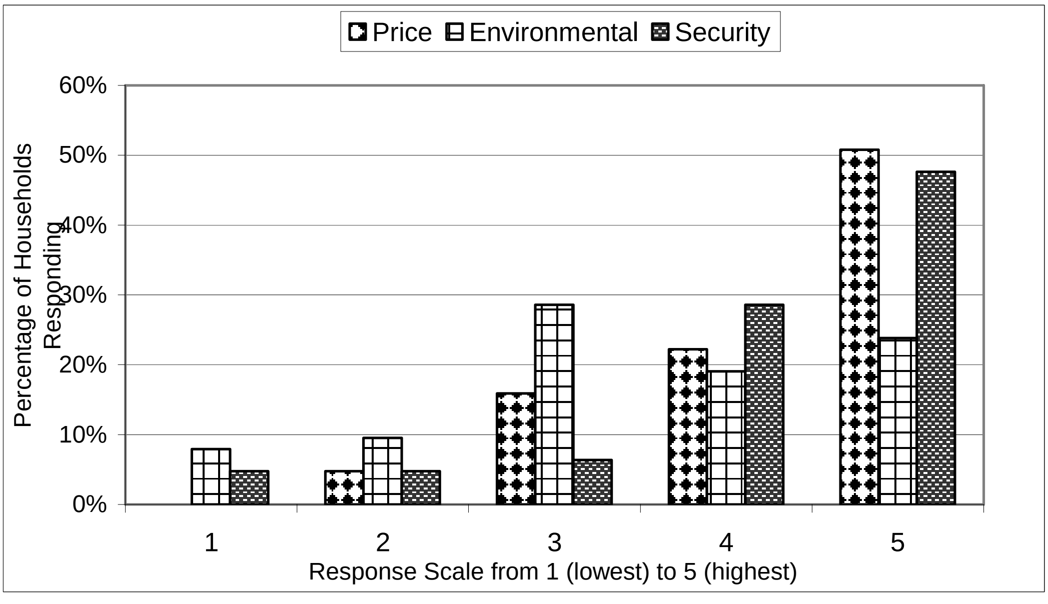

FIGURE 2: Household participants’ response rate to the three motivation factors, at each importance level

An importance weighting for each factor was calculated from the data using equation 1. The results show that that price is a stronger household behaviour change motivator (82%) followed by security (79%) and then the environment (64%).

To determine the responsiveness of the demand for electricity at peak times to the changes in the price, the environment (CO_2 emission) and security (blackouts), the following three questions were asked:

1. *If your electricity price were to go up, what percentage increase above your last bill would you consider to be large?*
2. *What percentage of non-renewable power generation (e.g. coal, gas, and diesel) would you consider to be too high?*
3. *How many power cuts on a winter morning or evening would you consider to be too many over the winter season*?

Table 2 shows the response of participants to these different scenarios. In Table 2, 60% of participants said that a 10% price increase would be considered high. This is a strong response to a small change and indicated by the large price responsiveness of 6.0. The number of participants with a low response to price change was very small, e.g. only 4% thought a price rise of more than 20% was high.

Just over one third of people said that 10% fossil fuel power generation would be too high. Cumulatively, the Christchurch customer tolerance for non-renewable generation is quite low, with 78% of participants indicating that 30% non-renewable generation is too high. This is interesting considering that it represents the current generation mix. This response may represent some misunderstanding of how the New Zealand power system operates. The environmental responsiveness ranges from around 3.5 to 1.8.

The tolerance for power supply disruptions was found to be very low for Christchurch residents. This is interesting as there have been very few power outages in the area. More than half of the participants stated that one power disruption was too many. According to the responsiveness equations, the responsiveness to supply security ranged from 62 to 38.

Price Increase During Peak Time	**10%**	**20%**	**30%**	**40%**	**50%**	NA
Households Responding	60%	32%	2%	2%	0%	4%
Cumulative Response	60%	92%	94%	96%	96%	4%
Price Responsiveness	6.0	4.6	3.1	2.4		
Non-Renewable Fraction During Peak Time	**10%**	**20%**	**30%**	**40%**	**50%**	NA
Households Responding	35%	33%	10%	6%	5%	11%
Cumulative Response	35%	68%	78%	84%	89%	11%
Environmental Responsiveness	3.5	3.4	2.6	2.1	1.8	
Security of Supply: Number of Power Cuts	**1**	**2**	**>2**			**NA**
Households Responding	62%	14%	14%			10%
Cumulative response	62%	76%	90%			
Security Responsiveness	62	38	NA			NA

TABLE: 2 Satisfaction levels of participants, to the factor variations

5. Discussion

Researchers in demand response need to recognize that high prices alone will not necessarily create the conditions needed to achieve effective peak demand management that could be reliably deployed to reduce the need for generation and transmission infrastructure. A range of factors could be used to influence people’s energy use behaviour but price is the only factor that has been used internationally. The objective of demand response is to reduce electricity demand during peak hours. The reductions are temporary and may represent simply shifting to an off peak time, improved efficiency, conservation or change of activity. The benefits of demand response to consumers in all sectors include lower peak price, market discipline, reliable electrical service and possibly lower environmental emissions. Better explanation of all these benefits to the consumer is necessary to achieve effective demand response in the residential sector. This study has shown that people would be motivated to reduce their electricity demand at peak times if they are informed about the consequences of meeting their demand at peak times. Our experiment has shown that people would be motivated by environmental and security factors to reduce their electricity demand at peak times. More research is therefore required to understand how people would behave in terms of reducing their electricity demand if feedback information on environmental emissions and system security are sent in real time to households as it has been done for price.

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