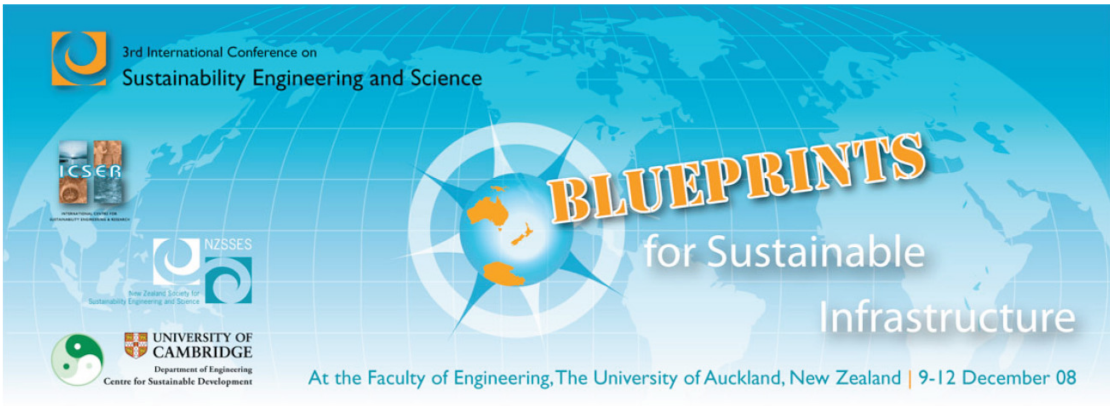


Demand Response in the Residential Sector: A Critical Feature of Sustainable Electricity Supply in New Zealand

Samuel. Gyamfi, B.Sc. Eng (KNUST), M.Sc. Energy (Aachen)
Susan. Krumdieck, Assoc Prof., BS, MS(Ariz. State), PhD(Colorado), MRSNZ
Advanced Energy and Material Systems Laboratory, Department of Mechanical Engineering, University of Canterbury, Private Bag 4800, Christchurch, New Zealand

Larry. Brackney, Senior Lecturer, BSME(RHIT), MS(RHIT), PhD(Purd.)
Electrical and Computer Engineering Department, University of Canterbury, Private Bag 4800, Christchurch, New Zealand

Abstract

The world summit on sustainable development in Johannesburg concluded that changing unsustainable patterns of energy use is a key area for global action to ensure survival of our planet. Demand response in the residential sector can play a key role in ensuring a secured and sustainable electricity supply by reducing future investments in generation and interconnection capacity and hence reducing the growth of electricity price and the development impacts on land and CO2 emissions. Further, demand response capability would increase the resilience of the power supply system to shortages, thus improving the security of supply and energy services. Demand side management has been used successfully over several decades to manage base-load demand growth, and to shift loads from peak to off-peak times. Demand response to reduce consumption at peak times on the network has been largely aimed at large industrial and commercial users. Information barriers and the lack of understanding of residential consumer behavior in responding to price signals has impeded development of effective response strategies and new enabling technologies in the residential sector. In this paper, we discuss some of the key social and behavioral issues that are being explored in order to achieve effective demand response. The research objective of the present work is to explore the peak hours demand response elasticity to price, environmental impacts (CO_2 intensity of generation), and social factors (risk of brown-outs and black-outs). These three elasticities are being measured by surveys of different residential households using a survey designed for the purpose. The project aim is to use this information, plus modelling of household activities and energy services to develop concepts for innovative engineering solutions to demand response through targeted communication of information about the supply system.

Keywords: Demand Response, Sustainability, Human Behaviour

1) Introduction

The residential sector is responsible for nearly one third of electricity consumption and the related emissions into the atmosphere from New Zealand's coal (7-12%) and gas (18-26%) generation. In New Zealand, the residential sector is the largest contributor to winter peak load, followed by the industrial and then the commercial sectors. Growing residential electricity demand is straining the available power distribution infrastructure, and meeting the peak demands in winter is increasingly expensive.

Short-term, responsive modification of residential electricity demand during peak times is a key to sustainable electricity supply. One of the key response modifications is lowering the peak-time consumption, as this generation has the highest CO_2 emissions. The other demand response is shedding of some residential loads when the peak demand is approaching the generation and/or interconnection capacity to assure supply security. There are numerous examples of small faults that have caused major power system outages when the demand on the network is near the capacity. On the supply side, spot market pricing for large users, ripple control and other timed circuits in all sectors have historically been used to shed load at peak times and shift load to off-peak. In the worst-case, distribution system operators need to use rolling black-outs to manage critically high peak demand.

Demand side management (DSM) has been important to electric utility planning and operation. Beginning in the mid-1980's, integrated resource planning through DSM projects resulted in considerable cost savings and improved grid security in the USA [Gellings and Chamberlin, 2002]. DSM involves planning, project implementation, and monitoring of measures designed to influence customer power consumption in ways that will produce changes in the power demand curve that reduce cost and improve security of supply. Demand response is a type of DSM aimed at short-term behaviour changes to reduce peak demand to maintain the safe margin between generation and/or distribution capacity and demand.

Information barriers and lack of understanding of residential customer demand response behaviour has impeded demand side management programmes that might provide effective peak demand response in the residential sector [DRRC, 2007]. Given the potential economic, environmental and security (blackouts) implications of peak demand, it is important to understand how residential customers may respond to external factors if they were informed in different ways. To date, efforts to reduce peak load have almost entirely been focused on specific components of the energy consumption system such as technology (physical characteristics of buildings and appliances) and price. However, experiments and studies on technology and price demonstrate that these factors alone would not help to achieve effective customer response.

Demand response addresses not only economic and security concerns but also environmental issues because of peak generation reliance on fossil fuels. This paper proposes that sustainable supply of power to households could be achieved at lower economic and environmental cost than generation alternatives through effective demand response. We further propose that this demand response could be achieved by broadening the scope of information conveyed to customers to include security (avoiding blackouts) and environmental impacts (CO_2 emissions) that are currently of concern to the residential customers. We will show why price response alone is not the optimal strategy for New Zealand. The result of customer response to peak load pricing for a typical residential feeder that supplies 400 households has been studied for a winter month of July, and the prospect of a novel signalling system incorporating the other two factors of environment and security is briefly discussed.

2) Electricity Supply and Demand in New Zealand

Supply Security

Security of electricity supply is the ability of the electrical power system to provide electricity to end-users with a specified level of continuity and quality in a sustainable manner, relating to the existing standards and contractual agreements at the points of delivery [EURELECTRIC, 2006]. Electricity supply security continues to be a problem in New Zealand. The margin of installed electricity capacity over peak load, which is often used as a measure of generation adequacy, has decreased since the introduction of deregulation [IEA, 2007]. Factors affecting security of electricity supply in New Zealand include dwindling natural gas reserves, tightening environmental standards, climate change, government policies, population and economic growth. The other important factor is winter lake levels, which can be out of step with electric energy demand during dry weather conditions. Table 1 gives a profile of the New Zealand electricity generation system for 2005.

Table. 1 Electricity Capacity and Generation Share, Year Ending 2005

	Capacity (MW)	Capacity Share %	Generation Share %
Hydro	5345	60	64
Gas	1765	20	16
Coal	796	9	10
Geothermal	470	5	6
Wind	166	2	1
Oil	155	2	0
Combustible Renewable, Waste and others	177	2	2
Total	8874	100	100

Electricity Demand

The total residential sector electricity demand in New Zealand has declined since the early 1970s by about 9.7 %, while at the same time the absolute demand value for the sector grew by about 70% during the same time frame. Total demand for all sectors grew from 15.9TWh in 1973 to 37.1TWh in 2005 [IEA, 2007]. Total demand for electricity is expected to grow by an average of 1.4% per annum over the next seventeen years, increasing to 48.3TWh[1] by 2025 [NZ Treasury 2004]. Growth is projected to be higher in the residential sector, which is currently the second largest consumer of electricity representing approximately 34% and estimated to contribute about 50% to peak load [Electricity-Commission, 2007]. Much of this growth is

[1] 0.2778TWh is equivalent to 1TJ

going to come about as a result of government policies such as the health policy program that requires households to remove older wood fuel appliances for space heating and encourages installation of electric heat pumps. This policy may have an impact on winter peak load and total electricity demand. Currently, electric heating load is met by resistance heating, so the switch of wood heating to electric heat pumps may be somewhat off-set by switching from resistance heaters to heat pumps.

Household price
Household price of electricity has been growing at an average of about 7 % per annum over the last six years. Average price (including tax) per kWh in 2006 was NZ$ 0.2024 [IEA, 2007]. Nevertheless, New Zealand is one of the countries among the OECD with low household electricity price as seen in Figures 1 and 2. Though price increase can foster electricity savings in the residential sector, the level of price at the local level is very high if the purchasing power standard of customers is taken into consideration (see fig. 2). High electricity prices are increasingly a social issue, in particular, with regard to lower income households. As a consequence it is possible to say that price increase will be limited by social factors and not by efficiency.

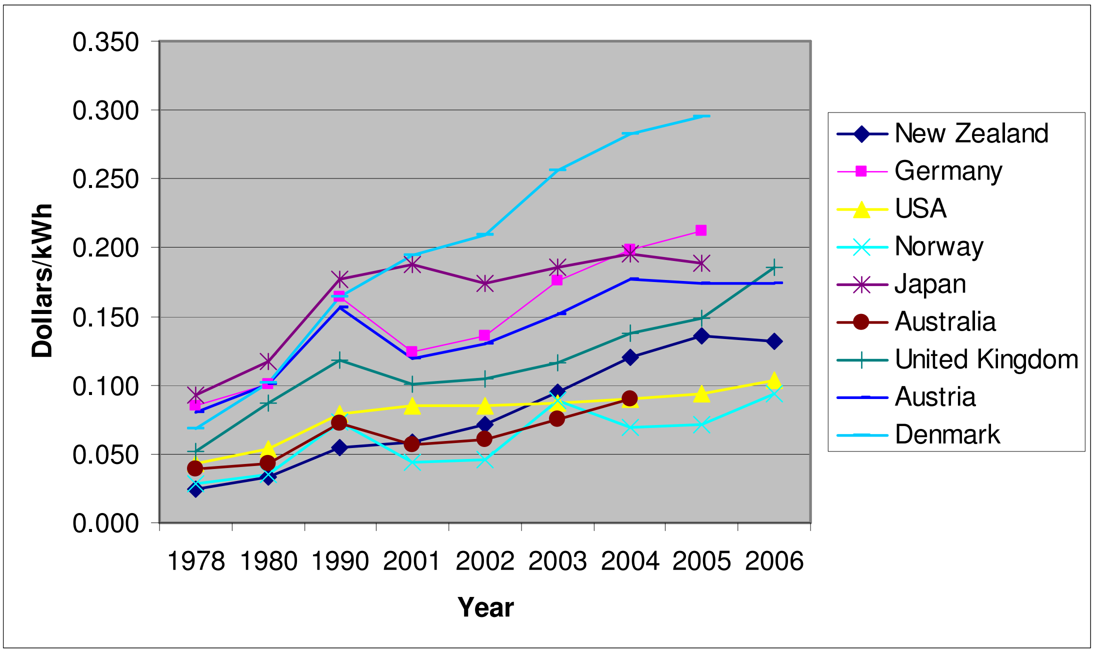
3) Demand Response in New Zealand

Demand response is a Demand Side Management (DSM) tool that is used to shift load from peak to off-peak hours, to reduce peak demand and to reduce energy consumption. Unlike the traditional automatic load control measures such as ripple control, demand response involves real-time customer choices about their electricity usage in response to signals from the utility. Demand response in New Zealand has, in the main, been restricted in the energy market to the large industrial users [EECA, 2004]. In the residential sector, there has been a long history of ripple controlled load management to control high electricity consuming equipment like hot water cylinders and pool pumps. Figure 3 shows representative load of a typical residential feeder that feeds a suburb with about 400 households in Christchurch in a winter month of July, 2006. The residential activities of heating, lights and cooking are apparent in the morning (11-19) and evening (33-39) peak loads. The two late night peaks are due to the night-time managed loads of water heaters and night-store heaters in this area.

4) Peak Load Demand Response

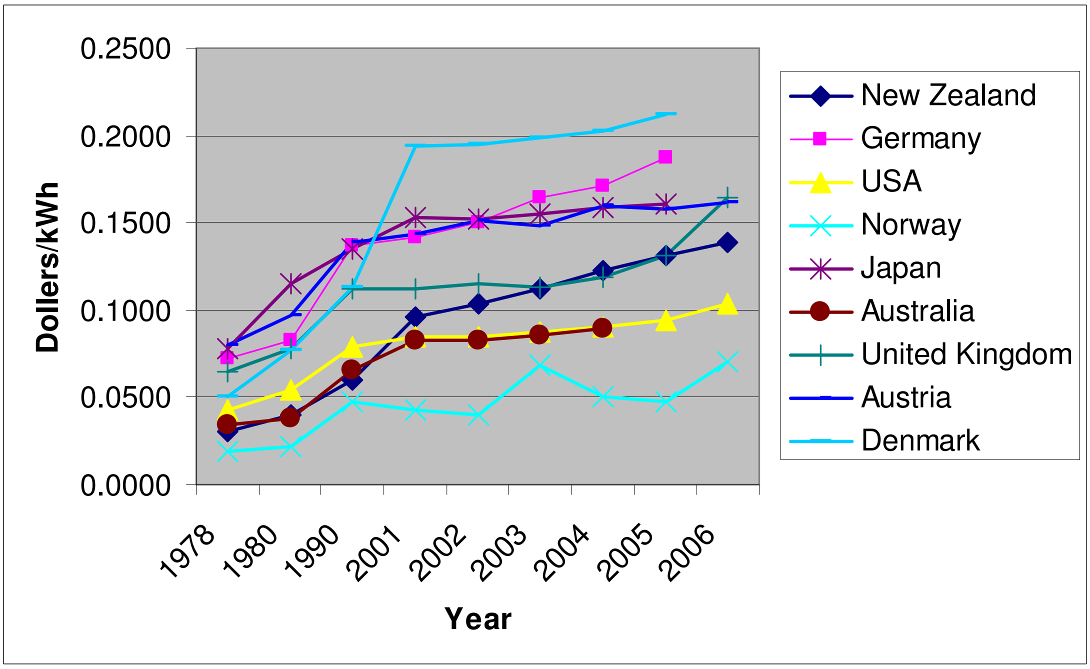
Current framework for addressing peak load
Currently, demand response is defined as “changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized” [USDOE, 2006]. It gets customers to reduce or shift load at a peak time by exposing them to variable pricing that is reflective of the cost of providing electricity. This is said to give residential customers sufficient financial or other incentive to reduce load at particular times. This type of tariff is being considered by many utilities in New Zealand to replace uniform tariffs that are currently used in the residential sector. Is this alone sufficient to induce household customers to change their behaviour to reduce load at a peak time? Is this compatible with all objectives of rate design; for example social equity and affair apportionment of cost among customers [Bonbright et al., 1988]?

Fig. 1 Household Price of Electricity (US$) Compared with that of some OECD Countries



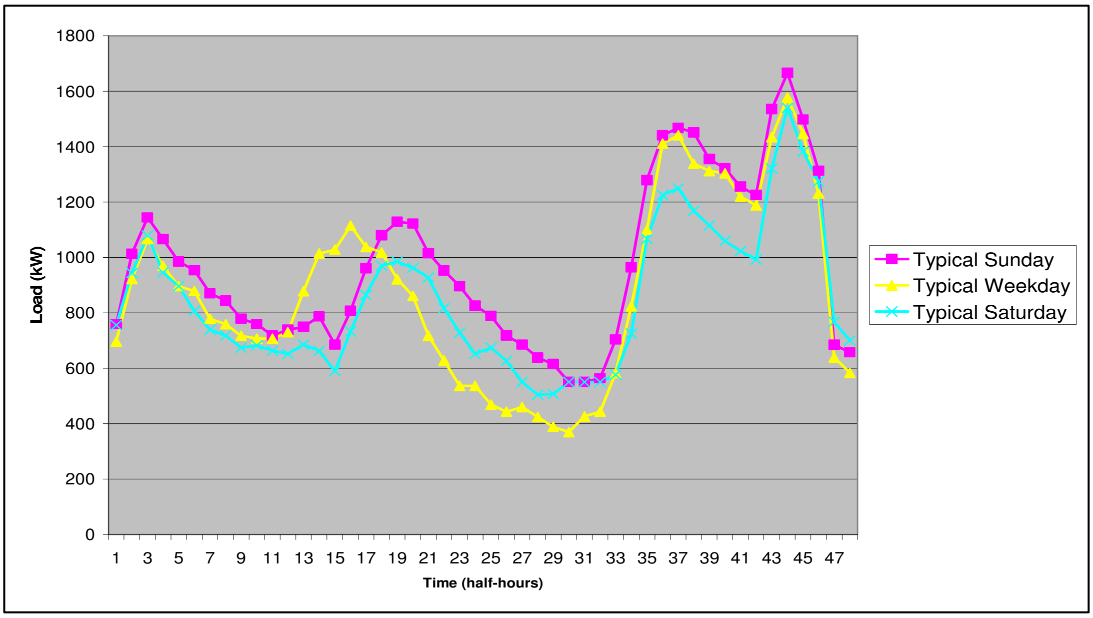
Source: IEA Electricity Info. 2007

Fig. 2 Household Electricity Price of some OECD Countries Converted, with Purchasing Power Parities



Source: IEA Electricity Info. 2007

Fig. 3 Residential Load characteristics for about 400 households in the winter month of July, 2006



Background on price demand response

Studies on price response employ different rate structures such as time-of-use (TOU), critical-peak-pricing (CPP), and real-time-pricing (RTP). The analysis of residential customer response to pricing has involved estimating the magnitude of customer load changes and the value of elasticity parameters that characterize customer degree of price responsiveness. Before one can understand the effect of price on peak demand, it is important to understand the basis of the price concept and how it has been applied to influence domestic energy consumption.

The pricing mechanism is based on the economic theory of consumer rationality. Economists view individuals as having preference that they seek to satisfy as fully as possible through purchases of goods and services given the constraints imposed by their income and market conditions. They view rationality as a fundamental axiom of human behavior; accordingly, energy-related decisions must be rational if analyzed correctly, and policy interventions such as equipment performance standards and demand-side management programs are likely to impair economic efficiency by depriving consumers of desired options [Sanstad & Howarth, 1994].

Engineers and behavioral researchers, in contrast, argue that consumer real-world decisions deviate from the ideals of preference maximization. They support their argument with empirical evidence that show frequent failure of household consumers to obey the assumption of consumer rationality. Several demand response studies reveal this last point [Heberlein & Warriner, 1982, Reiss & White, 2001]. Sociological and anthropological studies have, on the other hand, demonstrated the importance of social context in understanding domestic energy consumption; for example in development and up-take of household appliances. Our research is based on the energy systems engineering perspective that demand arises from activities, and so the energy services used during activities must be understood in order to understand how and why people might behave differently than normal and what kind of information or signal would affect this change.

Limitations of current models
Price response models which are used to address peak demand do not consider other factors that enable or constrain consumption. In these models, human behavior related to the use of electricity is seen as a step function of price. The underlying factors that inform the prices are not known or revealed to consumer. However, empirical evidence suggests that quite a large proportion of household consumers do not respond to price**.** There is also evidence that the threshold effect exists in price response and that beyond a certain price level, the effect of price increase is not as great as personal commitments or other non-price variables [Fitzgerald & Sanders, 1998, Heberlein & Warriner, 1982].

A combination of economic (price) and engineering models that together constitute a physical-technical-economic model (PTEM) might not fully address peak demand as the central role of human behavior in shaping households energy use may not be fully represented. These models (normally used in energy policy development) overestimate the importance of economic and technology solutions while underestimating the importance of social and non-economic influences [Lutzenhiser, 1993]

Individual decisions to conserve energy are motivated by internal factors: intrinsic satisfaction, guilt and moral responsibilities for energy use, and commitment to conserve [Seligman et al., 1979]. External influences include socio-economic, environmental, social and legal infrastructure, and supply security [Schipper et al., 1989]. Because the objective to reduce peak demand is broad and includes environmental, security as well as other concerns, the hypothesis of this research is that that effective demand response could be achieved by broadening and possibly targeting the type of information that is conveyed to households to include environmental and security constraints.

5) Theory and Response Model

Proposed framework of three-factor elasticity; cost, environmental, social
We define demand response broadly as electricity consumer responding to external indicators by changing their normal electricity usage patterns. These changes will involve changes in the normal activities and behaviors of members of a household during peak demand hours. In Christchurch, New Zealand, where our study will take place, the peak hours are in the winter heating season on weekday mornings as people prepare for work, and in the late afternoon and early evening as families prepare meals do the washing up. The theory for this study is that there are different classifications of residences that will respond in different ways to the range of signals. The framework of household classifications and response characteristics is shown in Fig. 4 along with the different ranges of activity response and demand elasticity.

Response model
Based on customers responses to these factors, a demand response signal will be developed to convey CO_2 emission information that relates the extra fossil fueled power plants and local diesel generators that are brought into service at peak times. Similarly, the likelihood of system outages (often measured by loss of load probability) is by far greatest at peak times [Kahn, 1988]. This information will be conveyed to the residential customers together with information on prices of electricity at peak times. Figure 5 shows the characteristic of the proposed price, CO2 and security information that will be conveyed to customers.

Fig. 4 Framework of Residential Households and Characteristics of Response to the Three Supply Factors, Cost, Environment, Social

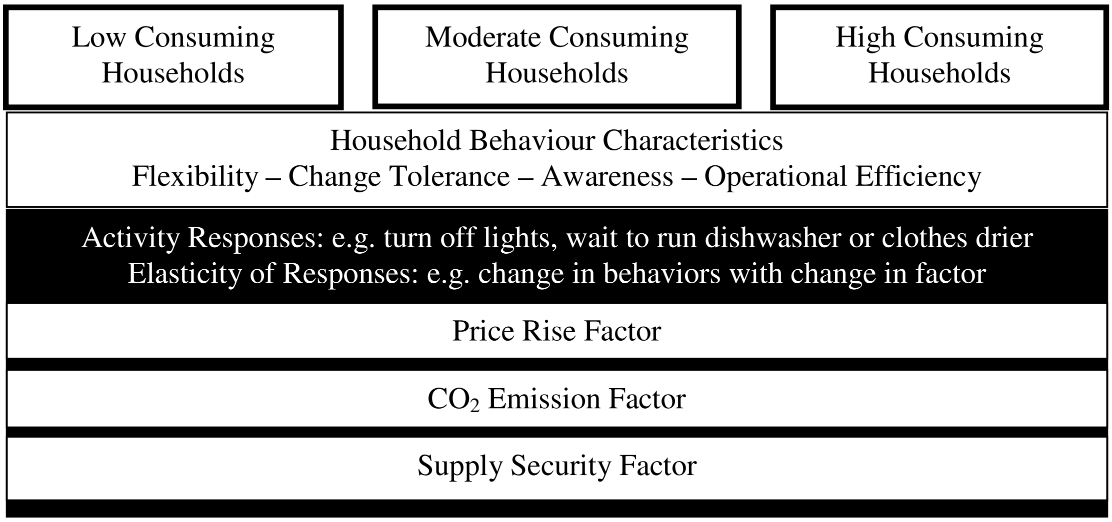
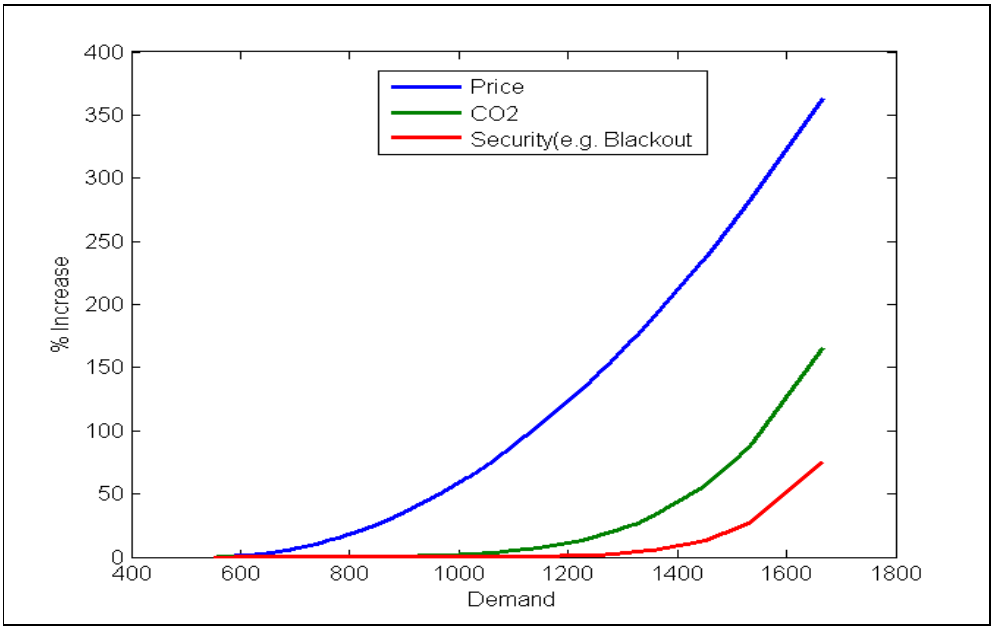


Fig. 5 Characteristics of the Proposed Price, CO2 and Security Information to be conveyed to Households



Impact of peak/off-peak pricing

Elasticity of substitution shows the % shift of demand from the peak to the off-peak period based on % increase in price of electricity at peak times. If the elasticity of substitution is 1, a peak to off-peak price ratio of 1.5 will result in peak to off peak demand ratio of 1.5.

$$E_{subs} = \frac{-\%\ \Delta(Q_p/Q_o)}{\%\ \Delta(P_p/P_o)}$$

A survey conducted as part of the Household Energy End-Use Project (HEEP) estimated elasticity of substitution as between +0.25 and +0.35 for Christchurch. For the lower limit case, reduction in peak load would be 12.5% (i.e. 0.25*0.50). In the high response case, reduction in peak demand would be as high as 17% (i.e. 0.35*0.50). This level of price demand response would have the effect on a typical residential load as shown in Table 2. It is clear that the kind of load shedding needed to stabilize the power system as demand approaches supply is not possible through normal price signals. Currently, the power distribution company in Christchurch uses electric water heating ripple control during peak to shed up to 88% of water heating on its network.

Table 2. Effect of Peak/off-peak pricing on a typical residential feeder for the winter month of July, 2006

	Half-Hours	Average Load kW	Maximum Load kW	Minimum Load kW
Without Demand Response				
Peak	630	1171.34	1779.26	883.59
Off-peak	758	741.88	879.44	232.34
Peak to off-peak ratio	0.83	1.58	2.02	3.80
With 25% Substitution Elasticity				
Peak	551.25	1024.93	1556.85	883.59
Off-peak	852.75	834.62	879.44	261.38
Peak to off-peak ratio	0.65	1.23	1.77	3.38
With 35% Substitution Elasticity				
Peak	522.90	972.21	1476.79	883.59
Off-peak	886.86	868.00	879.44	271.84
Peak to off-peak ratio	0.59	1.12	1.68	3.25

6) Experimental Approach

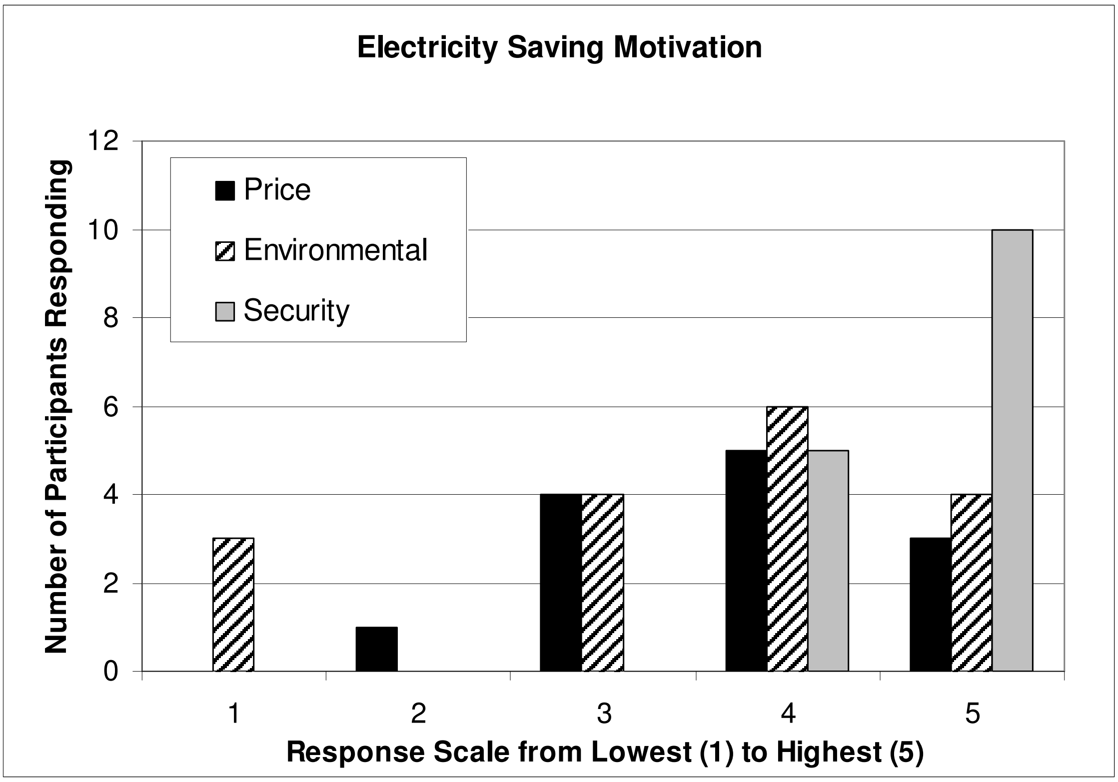
Experimental determination of three-factor elasticity

In order to test out the theory and verify the framework, a survey was designed to link normal peak hour activities to energy services. Survey questions examine the response of residential customers to three indicators: price, CO_2 emissions and system security. This is important because when electricity supply is constrained by generation, transmission and distribution capacities, and carbon emissions constraint, sustainable supply of power would not necessarily be achieved with high prices, especially if the customers' desire to use electricity is a stronger incentive than the price they have to pay.

The survey will be conducted in a suburb of about 400 households in Christchurch. This suburb has a residential feeder. The aim is to examine residential customers' response to this type of information and the impact that it will have on the residential feeder. The effect of this information is investigated by analyzing a range of consumer elasticities of demand in response to increase in price, CO2 emissions and a decrease in grid security (e.g. increase blackout) scenarios in winter in Christchurch. The survey is presented in Appendix A.

The survey was field-tested with a group of about 30 Christchurch residents in June 2008. The residents had voluntarily attended an advertised seminar given by Dr. Krumdieck about sustainability. A good number of the attendees were couples or from the same household. The response rate of 15 surveys mailed back after being completed at home is reasonably good. The surveys were all completely filled out. As a preliminary look at elasticity to different factors, the survey data was analyzed according to the willingness and number of responsive activities reported. The results shown in Figure 6 indicate that the response to the risk of power disruption during peak demand times may be an interesting new area for energy management work. The results also demonstrate an interesting "green" response with the indication of higher CO_2 emissions equal to or exceeding the price response.

Fig. 6 Results of Preliminary Survey of Christchurch Residents



7) Conclusion

Demand response is a demand side management approach that addresses the specific problem of peak demand. In the residential sector in Christchurch, peak demand response will require people to interrupt their normal morning or evening activities in the winter, including lighting, cooking, washing and heating. The aim of the research project reported in this paper is to understand the activities and power demand in the residential customers in Christchurch, New Zealand, and to develop a demand response plan to achieve in the range of 20kW of peak load shedding for a typical residential feeder of 1800 kW peak demand. The project hypothesis is that environmental and security response will need to be used in addition to price to meet this aim. Peak time price rises, aimed to induce households to change their electricity using routines, are not likely to be successful in reducing peak load significantly.

While a certain fraction of the population may be price-responsive, they may also be the lower income, and lower power users. We propose that a fraction of the population would respond to information that the peak demand has caused diesel generators in the city to be switched on, thus increasing local pollution and CO_2 emissions. Further, we have made the argument that a significant segment of the population would respond to information that there is a risk of brown-out or black-out. The form of the response will depend on the information conveyed to the customer. In other words, getting a high response would mean sending clear information to the right responders. Also, whatever method we use to reduce peak load must satisfy the three sustainable conditions as proposed by [Barbier, 1987]: economic viability, social acceptability and environmentally sustainable.

The core objective of demand response should therefore be focused on reducing peak load and should be consistent with sustainable goal of achieving environmental quality, economic efficiency and system reliability. This could better be achieved by broadening the scope of demand response signal to convey environmental and security constrains that limit delivery of electricity at peak times. Our current research is measuring the cost, environmental, and security demand response for residential households in Christchurch, and modeling the aggregate demand curve modification that could be realized.

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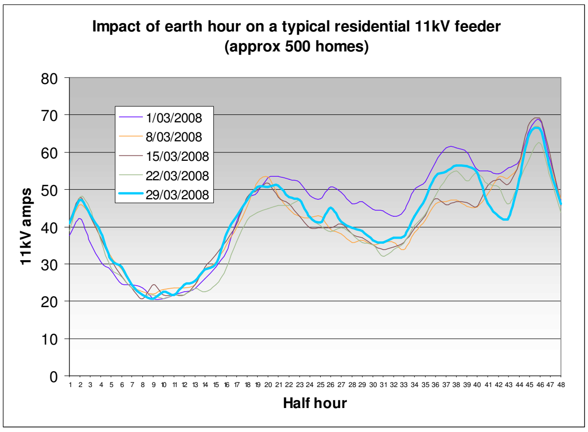
APPENDIX A

Why reduce electricity during peak demand?

Like roads, electricity networks have limited capacity. The 'rush hour' on New Zealand electricity networks typically occurs on very cold winter evenings when people arrive home from work and turn on their lights and heaters. If electricity demand is higher than planned for, then there is a risk of power cuts.



One solution to these high loads is to expand the electricity network's capacity - much like making roads bigger to handle the traffic. However this solution is very expensive and would lead to an increase in the price of electricity. It could also mean an increase in environmental pollution through the use of high carbon emission sources of generation.

Because electricity 'rush hours', or 'peak demand periods', only occur for a few hours each year, the other cheaper solution is for customers to reduce their demand during these peak demand periods. Typically customers will reduce their electricity use during peak demand periods when they are given a price incentive to do so.

Future Change Issues

If your electricity price were to go up, what percentage increase above your last bill would you consider to be large?

[ ] 10% [ ] 20% [ ] 30%

[ ] 40% [ ] 50% [ ] above 50%

What percentage of non-renewable power generation (e.g. coal, gas and diesel) would you consider to be too high?

[ ] 10% [ ] 20% [ ] 30%

[ ] 40% [ ] 50% [ ] above 50%

How many power cuts on winter mornings or evenings would you consider to be too many over the season?

Energy Saving Motivation

Please indicate how important you consider each of the following factors as a reason to reduce your electricity use for a designated period.

	Not important			Very important	
Price	1	2	3	4	5
Environmental: (e.g. carbon reduction)	1	2	3	4	5
Supply Security (e.g. black out)	1	2	3	4	5