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# DEMAND RESPONSE IN LOW-CARBON POWER SYSTEMS: A REVIEW OF RESIDENTIAL ELECTRICAL DEMAND RESPONSE PROJECTS

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## ABSTRACT

The transition to a future low-carbon power system will increase the need for and value of demand response – where demand can be curtailed or shifted in time according to the network's requirements. The electricity supply industry is investing heavily in 'smart' technologies, partly based on the assumption that demand response will be available when it is needed, yet this is an unfamiliar concept to most consumers, who still view electricity as a resource that can be consumed as and when they want it. That such a gap exists between the reality on the ground and the requirements of the future is a cause for concern, yet the methods proposed today to achieve demand response are based predominantly on assumptions that people will accept and respond to variations in the price of electricity. There is however growing evidence that the 'people are economic actors' approach is inadequate when dealing with the complexities of energy-use within the home. This paper reviews existing residential demand response projects, and supports the growing realisation that the principal challenge in demand response is no longer the technology itself but rather its acceptance and use by the consumer. In order to deal with this challenge, a more holistic approach to demand response is needed, one that can better deal with both the 'hard' and 'soft' sides of the system.

## THE REQUIREMENTS FOR DEMAND RESPONSE IN LOW-CARBON POWER SYSTEMS

One of the fundamental challenges in electrical power systems engineering is the need to maintain a continuous balance between power supply and demand (Wildi 2000, p. 638). Any discrepancy between these will manifest itself in a change in the AC frequency of the system or 'grid'. In order for the grid to function effectively, the frequency needs to be maintained within strict limits of its nominal frequency. The traditional approach to achieve this is based on 'predict and provide'; a central system operator

forecasts the expected demand and schedules generators to meet the demand in a manner that seeks to minimise the cost of supply ('optimum economic dispatch' (Freris, Infield 2008, p. 200)). The systems to balance supply and demand today are much more elaborate than this simple description (National Grid 2010), but fundamentally they are based on the same paradigm – balancing is predominantly achieved through scheduling, dispatch and response of relatively flexible fossil-fueled power plant.

This set-up has worked relatively well to date, but fundamental changes will be required over the coming decades. Governments have recognised the need to curb carbon emissions (European Commission 2010), which will necessitate action to decarbonise power systems. The UK itself faces the considerable challenge of reducing carbon emissions by 34% from their 1990 levels by 2020, and by 80% by 2050 (UK Government 2008). This will require that electricity generation become almost entirely decarbonised by 2030 (Committee on Climate Change 2009) and it is expected that this will be achieved predominantly through significant expansion in generation from nuclear and renewables (Department for Energy and Climate Change 2010a).

A future supply-mix dominated by nuclear and renewables poses considerable challenges to the task of balancing the grid. Nuclear power is relatively inflexible, and is most optimally run at constant output (Freris, Infield 2008, p. 23). Renewables such as wind power and solar power are, on the other hand, relatively uncontrollable and intermittent by nature (Nørregaard, Østergaard et al. 2009) – we cannot turn the wind on or off as and when we want to. As a result, any low-carbon power system dominated by nuclear and renewables will not be able to rely upon existing procedures for power balancing, as there will simply not be enough flexible generators to provide balancing services. Such a future will require a paradigm shift in the way the system is balanced. No longer will we be able to 'predict and provide', instead we will need more demand response (Strbac 2008) – in other words the ability to

control, or otherwise influence, the demand-side, shifting consumption towards periods of high output.

A low-carbon future therefore increases the value of a more flexible demand side (Nørregaard, Østergaard et al. 2009, p. 28). Yet this is an unfamiliar concept to most electricity consumers. The era of plentiful, trouble free supplies of fossil-fuel may be coming to an end, but the majority of consumers still view electricity as a resource that can be consumed as and when they want it. That such a gap exists between the reality on the ground and the requirements of the future is a cause for concern, and is the motivation for this research. The following section will look at the way demand response is being achieved today, in order to try to understand how to bridge this gap, and see how progress can be made towards a low-carbon future.

## REVIEW OF EXISTING DEMAND RESPONSE PROJECTS

In order to provide an overview of the different ways in which demand response is being achieved today, this section presents case-studies of six different demand response projects. Each case-study demonstrates a different approach to achieving demand response. The purpose of this section is to provide a brief summary of the individual projects and present their results. The lessons that can be learned from these projects will then be discussed in subsequent sections.

### **Radio Teleswitch System, United Kingdom**

The Radio Teleswitch (RTS) system was developed in the early 80s in the UK in order to provide a one-way radio-communications link between the electricity supply industry and the domestic electricity meters that were associated with off-peak electric storage and water heaters. These 'Economy 7' meters were traditionally switched using conventional time clocks embedded within the meter, however this suffered from certain operational problems that the supply industry wanted to overcome, such as the need to reset clocks after power outages, difficulties associated with changes from British Summer Time to Greenwich Mean Time (Woolner, Hannon 1996), and the creation of artificial demand peaks due to concurrent switching of heaters (McCartney 1993). By installing RTS receivers at the domestic meter, the signal broadcast by the Radio Teleswitch system could be used to switch meters between on and off peak rates, and thereby control when storage heaters would be turned on. The RTS system therefore served as a flexible alternative to the conventional time clocks, as well as a

demand side management tool, capable of smoothing the artificial peaks in demand. RTS facilitated the introduction of flexible tariff options for storage heaters, for example the 'Economy 10' tariff, which allowed up to 10 hours of non-continuous charging throughout the day and night. Given that off-peak rates applied to all usage, not just storage and water heaters, it was required that consumers were informed about exact switching times in advance, which reduced the capability of the RTS system to smooth out the artificial peaks in demand (McCartney 1993). To resolve this problem, a 'twin element' RTS meter was developed and introduced in 1986 that separated the energy used by the storage heaters by placing it on a second meter element. Standard household consumption could therefore be switched according to pre-defined time periods, while the storage heaters could be separately controlled by the supply companies in order to provide the minimum of number of hours charge, though at times that were dynamically managed by the supply industry.

### Results

The number of houses in Great Britain with electric storage heaters has varied considerably over the past decades: from 1.1M in the early 1970's, to a peak in the late 1990's of 2.2M, and a subsequent fall to 1.1M by 2007 (Department for Energy and Climate Change 2010b). Taking into account the increase in total number of houses, this represents a drop from 20% penetration of storage heaters in 1970, to 5% in 2007. By contrast, there were 5.3M Economy 7 meters in 2008, or 19.8% of the installed meter population (Department for Energy and Climate Change 2009), indicating that approximately one in five Economy 7 customers do not have storage heaters. This would seem to suggest that whilst the notion of cheap off-peak electricity has proved popular, electric storage heaters themselves have not. Indeed this apparent aversion was highlighted in a recent Omnibus survey (Ofgem 2010), which found that the use of electric storage heaters was the least popular method of shifting electricity usage to cheaper periods of the day (heating water at different times of the day being the most popular). Interestingly, there was a strong correlation between aversion to storage heaters and age – 60% of the 65+ respondents said that it was 'very/fairly unlikely' that they would use storage heaters compared to 28% of 15-34 year olds. The number of storage heaters that can be controlled by Radio Teleswitching is therefore on a downward trend. Despite this decline, the Radio Teleswitch system has recently been upgraded (Cygnet Solutions 2010), and indeed

its application in innovative demand response schemes is the subject of ongoing research (Scottish Power Distribution 2010).

### **Ripple Control System, Czech Republic**

The Ripple Control System was developed by the three Czech electricity supply companies (CEZ, E-ON and PRE) over several decades prior to the deregulation of the Czech energy sector, and was used primarily to shape the residential demand profile so that it better matched the supplier's predictions, thereby minimising any potential trading losses (Neuberg 2009). The system consisted of automated control of residential consumers' electric heaters via centralised power line carrier signal communication. Applicable customers were offered two types of time-of-use tariff – an 8 hour low-tariff scheme for night-time storage heaters, and a 20 hour low-tariff scheme for direct-acting heaters. In return, customers allowed the supplier to block the operation of their heaters during on-peak periods. Both tariffs were operated such that the suppliers could specify (within regulatory constraints) when the off-peak periods would fall, allowing them to build load when appropriate during night-time troughs using the 8-hour scheme (turning on the storage heaters), and reducing day-time peaks using the 20-hour scheme (turning off direct-acting heaters).

The specific off-peak period times were communicated in advance to customers via the internet, who were able to take advantage of the off-peak tariffs to use other energy demanding appliances. Nonetheless, because the suppliers could dynamically change the off-peak time periods, this meant that customers had to constantly adapt their behaviour, which some perceived negatively.

#### Results

Approximately 20% of Czech customers are ripple control-enabled, corresponding to 2.5GW of storage heaters and 1.9GW of direct-acting heaters. Winter peak load in the Czech Republic is approximately 11GW in 2003. The Ripple Control system was used as an effective demand response system up until 2005, at which point the Czech energy market underwent deregulation. The previously vertically-integrated supply companies became separated into distribution and supply operations, and ownership of the Ripple Control system was passed on to the newly formed distribution network operators. Unfortunately however, one of the prime motivations to use the system had been effectively removed, as the system had been used principally as a tool for minimising trading losses, and this activity had now been separated from the distribution network

operator. As a result, the Ripple Control system is currently used primarily by the network operators in order to optimise network power flows and to reduce demands during network contingencies. These uses have been further constrained by legislative requirements that any use of the system be notified at least one week in advance (except for use during network contingencies), in order not to increase forecasting errors for the suppliers' electricity traders.

### **LIPAedge, Long Island, New York, USA**

The LIPAedge project was developed by the Long Island Power Authority (LIPA) – a non-profit utility – in order to reduce summer peak demand and provide a fast reserve service by using centralised control of residential and small commercial air-conditioning units (Kirby 2003). Participants in the project had programmable thermostats fitted to their air-conditioners, and the utility could then send commands requesting that the thermostat raise its temperature set-point or limit its duty-cycle for a limited period. Alternatively, the air-conditioning units could be commanded to shut off completely, in order to provide a fast reserve service. Two-way pagers were used to transmit the curtailment commands and to receive response and monitoring information. Utility control of the customer's thermostat could only happen during pre-notified critical peak periods, up to a maximum of seven days per year between the hours of 2pm and 6pm (Long Island Power Authority 2001).

Note that LIPAedge did not employ any form of innovative tariff structure. Participation was incentivised through a one-off payment to the customer, who got the added benefit of having a new configurable heating control technology installed in their property. Customers were able to access a programmable interface for the thermostat via the internet, this being one of the benefits of participation.

#### Results

As of 2003, LIPAedge was the largest residential load control program in the US that used two-way communications (Kirby 2003). Around 17,000 controllable units were installed and operational in 2002 and LIPA's goal was to achieve ~25MW of peak demand reduction from a total of 23,400 responsive loads by 2003. Typical system response was in the order of 90 seconds between a curtailment order being issued and acted upon by the loads, thus providing a fast reserve service. Customers could override the curtailment requests, except those called during network contingencies. Within three hours of a typical peak curtailment period, on average 35% of commercial

customers and 15% of residential customers had manually overridden their thermostats.

### Smart Price Pilot, Ontario, Canada

The Ontario Smart Price Pilot (OSPP) was initiated by the Ontario Energy Board (the state's energy regulator) in order to test the acceptance and response of residential consumers to a range of dynamic pricing schemes, which were aimed principally at reducing winter and summer peak demand (Strapp, King et al. 2007). Customers were enrolled into three different tariff test groups: a three-tiered time-of-use (TOU) tariff with on-peak, off-peak and mid-peak periods, and two critical peak tariffs that superimposed either a critical peak price (CPP) or critical peak rebate (CPR) on top of the OSPP time-of-use tariff. Customers on the critical peak tariffs were informed in advance about the exact times of the critical peak hours by their choice of email, text message or phone call. In addition, the time-bands of the peak periods for all three tariffs varied seasonally – the summer peak period (11am-5pm) changing to 7am-11am and 5pm-8pm during the winter. Participants were selected at random from the population that had already had smart meters installed. The program was unexpectedly over-subscribed and roughly 125 customers were assigned to each of the three tariff groups, with a further 125 customers assigned to a control group on a non-time-of-use tariff, used as a benchmark to measure the demand response (peak shift) and conservation (total energy reduction) effects amongst the test groups. The trial lasted seven months, including one summer and one winter. Four critical peak days were called during the summer period and three during the winter.

### Results

The pilot recorded a mix of results. Out of the seven critical peak days that were called, only the first two produced statistically significant shifts in peak demand measured in terms of the on-peak demand reduction for the three tariff groups combined (Table 1). Interestingly, one of the winter critical peak days produced an increase in peak demand – a counter-intuitive result. When looking at individual tariff test groups separately, the critical peak pricing groups did produce statistically significant reductions in peak demand (Table 2), though again only during the summer period. On non-event days – where all three test groups were effectively on the same time-of-use tariff – no statistically significant shifting occurred in the test groups with the exception of one of the critical peak test groups, which demonstrated an *increase* in on-peak demand. On average, there

was a conservation effect of 6% across the test groups for the full test period.

Table 1

*Shifts in consumption by all tariff test groups on critical peak days during the OSPP Project (Strapp, King et al. 2007). n/s denotes results that were not statistically significant.*

CRITICAL PEAK DAY (ENTIRE PEAK PERIOD)	SUMMER
Friday, August 18	27.7%
Tuesday, August 29	10.1%
Thursday, September 7	n/s
Friday, September 8	n/s
	WINTER
Tuesday, January 16	n/s
Wednesday, January 17	-7.2%
Friday, January 26	n/s

The pilot gauged participant feedback on the project through focus groups and surveys. Overall there was strong customer satisfaction (78% would recommend the time-of-use tariff to their friends), and participants felt that they were more aware of how to reduce their bill, had greater control over their electricity costs and that they were benefiting the environment. That said, many participants also expressed disappointment that their efforts had not resulted in greater savings on their bills. The majority of the participants (74%) preferred the time-of-use tariff over the critical peak tariffs, and 71% thought that the price differential between on-peak and off-peak was enough for them to shift consumption patterns. The feedback emphasised that the participants valued the fact that they had been given information about the various tariff structures in a clear, concise and durable form – in this case a refrigerator magnet depicting the different peak time periods in tabular form. Most found the time-of-use rates easy to understand and to adapt to, though many participants had difficulty remembering the start times of different peak periods. Some participants, such as those with young children or babies, found it difficult to adapt their behaviour, though they felt they were not being penalised under the time-of-use scheme. Some participants were concerned before the trial that the new tariffs could be a 'money grab' by the utility, though none felt this by the end of the trial. Many participants in the critical peak test groups felt that during the critical peak events, they had reduced their consumption to the bare minimum, and that they could achieve no more shifting.

*Table 2*  
*Shifts in consumption for individual tariff test groups on critical peak days during the OSPP Project (Strapp, King et al. 2007).*

	TOU	CPP	CPR
<b>PERIOD</b>	<b>SUMMER</b>		
Critical peak hours (3-4 hours during peak)	5.7%(n/s)	25.4%	17.5%
Entire on-peak period	2.4%(n/s)	11.9%	8.5%
Mid-peak	n/s	n/s	n/s
Off-peak	n/s	n/s	n/s
	<b>WINTER</b>		
Critical peak hours	n/s	n/s	n/s
Entire on-peak period	n/s	n/s	n/s
Mid-peak	n/s	n/s	n/s
Off-peak	n/s	n/s	n/s

### **Energy Smart Pricing Plan, Illinois, USA**

The Energy Smart Pricing Plan (ESPP) was a residential real-time pricing trial organised by the Community Energy Cooperative in conjunction with ComEd (a large utility) in Illinois, and which ran from 2003 to 2006 (Summit Blue Consulting 2007). ESPP was the first long-term residential consumer real-time pricing program, and was designed as a proof of concept with the objective of demonstrating the potential value of real-time pricing as a retail option. The expected benefits to consumers were: access to low (on average) wholesale prices, greater retail choice for customers, and greater control over their energy use. The expected benefits to the electricity network were to contribute towards reducing peak demand, thus lowering the overall cost of electricity, and to improve system reliability.

The 1,500 participants therefore paid wholesale prices for their electricity, with an additional cost for distribution, transmission and ancillary services. The key aspect of the scheme was that the tariff did not include the standard 'risk premium' usually added by the supplier to their retail tariffs to cover their trading risks (Star, Evens et al. 2008). As a result, the ESPP tariff was not designed to be revenue neutral, so that even customers who did not change their consumption behaviour could still expect to make bill savings. Consumers had access to indicative hourly prices on a day-ahead basis, although they paid the actual hourly prices that were applicable on the day. On high price days (>\$0.13/kWh), participants were sent notifications to warn them when these were expected to occur. In order to safeguard against extreme price rises, a price cap of \$0.50/kWh was imposed.

The goal of the ESPP was to shift the risk of wholesale prices from the supplier to the

consumer, thereby giving them the opportunity to capture the value of the risk premium. As a result, there was a certain degree of risk or uncertainty involved in the pricing system, which was born by the customer. Indeed, even though the differences between real-time and day ahead prices were reported to be minimal (Star, Evens et al. 2008), this uncertainty proved to be a barrier to recruitment uptake for the trial.

The Co-operative's objective in the program was '[to help] consumers and communities obtain the information and services they need to control energy costs'. Participants were given information about the general shapes of wholesale prices by season, as well as energy efficiency information and advice on how to reduce peak demand. Web-based tools were also provided to allow access to energy usage information.

### Results

The ESPP proved that customers could accept and respond to real-time pricing, and laid the foundations for the mandatory inclusion of a real-time pricing retail option for consumers in Illinois from 2007 onwards (Star, Isaacson et al. 2010). The project found that the participants price elasticity of demand stayed relatively constant over the course of the program (Table 3), and that their response increased during high price periods due to the sent notifications. The program found that lower income households tended to be more responsive than higher income households. On consecutive high price days, or when the length of the high price period increased, the ESPP found that customer response trailed off, and needed a period without notifications in order to 'recharge'. In addition, participants tended to respond less during the day, and more in the late afternoon and evening. Customers achieved yearly bill savings of 10% over the program period, though in 2005 they suffered a bill increase of 6% due to high wholesale prices, reflecting an unusually hot summer and high peak demands. The program experienced high retention rates in excess of 99% for most years, with high levels of customer satisfaction. 80% of participants felt that participation was 'quick and easy'.

*Table 3*  
Annual elasticity of demand for ESPP participants, 2003 – 2006 (Summit Blue Consulting 2007)

YEAR	OVERALL ELASTICITY
2003	-4.2%
2004	-8.0%
2005	-4.7%
2006	-4.7% (<0.13c/kWh)
	-8.2% (>0.13c/kWh)

### **Gridwise™ Olympic Peninsula Project, Washington, USA**

The Gridwise Olympic Peninsula Project was managed by Pacific Northwest National Laboratories, and ran from 2006 to 2007 (Hammerstrom 2007b). The focus of the project was to test and demonstrate how smart grid technologies could enable residential consumers and distributed generators to support active network management. One of the main focuses of the project was the demonstration of a 'local marginal energy price market' – a near-real-time electricity market in which residential loads could bid for their demand and distributed generators could offer to supply power. Programmable thermostats were fitted to residential loads such as air conditioning units and electric water heaters, and these would calculate the market price at which they would be willing to curtail their demand. This information was then sent to a central market controller, which, given information about the offers and bids of all the participating loads and generators, would then calculate the market clearing price. The market clearing price would then be sent to all the market participants, effectively signalling them to either turn on or shut off. The market was cleared every five minutes, a time period chosen so as to match the natural cycle time of the loads. This system of programmable thermostats participating automatically in a real-time electricity market was termed 'transactive load control' and successfully demonstrated how residential loads could provide 'smart' system support using real-time pricing as a control signal.

In total, 112 homes participated in the project, and had energy-management systems fitted which allowed two-way communications between the market and the loads' thermostats. Participants were assigned to a control group, a fixed price group, a standard two-tier time-of-use tariff group, and a real-time pricing group. Only the real-time pricing group participated in the real-time energy market. These participants were able to set their preferences such as their occupancy profiles, and what loads could be

controlled by the market price signal. They were further able to specify their preference for cost over comfort. These cost/comfort choices established acceptable temperature limits for water and space heating and so allowed the project to assign response curves for each load that allowed their participation in the market. This meant that the 'complicated maths' involved in calculating demand bids was performed automatically, based on relatively simple user choices between cost and comfort balance.

### Results

The project did not publish exact figures for peak demand reduction for the different tariff groups, however indicative values have been estimated from the published load profiles (Hammerstrom 2007b) and are given in (Table 4).

*Table 4*  
Results of the OPP project (Hammerstrom 2007b).

	TIME-OF-USE GROUP	REAL-TIME PRICING GROUP
Total reduction in demand	-17%	0%
Peak demand reduction (winter week day)	-24%	-9%

On average, the participants on the time-of-use tariff achieved greater reductions in peak and total demand than the real-time pricing group. Indeed, there appeared to be no conservation effect at all with the real-time pricing group (those that participated in the real-time energy market).

Although the real-time pricing participants were put on a 'balanced economy/balanced comfort' preference setting as a default, 39% of the participants changed their water heater settings to 'no price reaction', and 22% did the same for their air conditioners. The project organisers believed that this may have been due to a problem had occurred with the programable thermostats that occurred early on in the project, and that caused some participants to disallow any further control by the project.

## DISCUSSION

The previous section revealed that the principal objective of demand response projects is to enable the consumer to participate in the wholesale electricity market in some way that will benefit the overall system stability or efficiency. This can be achieved by simplifying market participation for the consumer – either by automating their response (Radio Teleswitch, Ripple Control, LIPAedge, Gridwise), or by providing the consumer with a simplified market price signal (OSPP, ESPP). In each case, the consumer was incentivised for their participation, either through the potential to reduce their bills, or by receiving new equipment. The important question is whether automation and simplified price signals will be sufficient for enabling demand response on the required scale for a low-carbon future.

### **Limitations to automation**

Automation was the key to the operation of four of the above case-studies: Radio Teleswitch, Ripple Control, LIPAedge and Gridwise systems. In each case, the consumer ceded control of some of their appliances to a centralised or distributed controller. It is important however to look at some of the issues that automation raised in these projects, in order to understand how much of a role automation could play in future demand response projects.

One of the challenges facing proponents of automation is the difficulty of automating the many types of appliances beyond heaters. People will be likely to reject automation of their cookers and TVs for example. It is unlikely that automation could be used to 'invisibly' shift these types of loads. This problem was highlighted in the Gridwise project, which demonstrated that, although automation could provide a useful tool to allow appliances to respond on behalf of consumers to rapid variations in price in an 'invisible' way, it also came at an apparent cost - the participants benefitting from the automation technology did not achieve any total demand reduction, and even achieved less peak demand reduction than the participants on the time-of-use tariff. This would indicate that the participants did not change their behaviour beyond allowing the automation technology to be installed in their home. It is important therefore to understand the context in which technology is being introduced, and to realise what impacts this may have on the consumer – if the technology makes people complacent, and less likely to change their behaviour in other ways, then we need to understand how and why this might occur.

Another challenge with automation is that, in order for it to work, it must first be accepted and

used by the consumer. This is a non-trivial matter – people can react negatively to having aspects of their private lives controlled. Participants in the Ripple Control system apparently were inconvenienced by having the timings of the off-peak periods constantly changing. In the UK, the apparent unpopularity of electric storage heaters, and the consequent decline in their numbers, is reducing the potential for Radio Teleswitching to smooth the national load profile. In the Gridwise project, many participants stopped allowing their appliances to be controlled, in this case because of a fault in the control equipment. Perhaps the participants felt there was too much uncertainty involved in having their appliances respond to real-time prices in complicated ways that they may not have fully understood. If consumers act in a 'once bitten, twice shy' manner, then this bears consideration given the fact that the more complicated the control system, the more likely something will go wrong with it.

The evidence therefore points to there being an important role for automation in demand response, though one that needs to be developed with a greater understanding of the impacts it might have on the consumer. Control strategies need to be sympathetic to consumers, and allow them to retain enough control so that 'Big Brother' fears are not encouraged, while at the same time not over-complicating things for the consumer. Certain types of automated technology would therefore seem to make sense, such as frequency-sensitive appliances (Hammerstrom 2007a) where the consumer would be largely unaware of when a control action had been taken. The Gridwise concept, where customers can choose their preferences on a sliding scale between 'economy' and 'comfort', also fits well with this notion of 'customer-friendly' automation. It should be clear however from the apparent slow demise of the electric storage heater in the UK, that however smart the technology, the key challenge is rather whether it will prove to be acceptable to the consumer in the real-world, and how they will end up using it.

### **Is price an effective tool to enable consumer response?**

The two case-studies that focussed specifically on price and how consumers responded to it were the Ontario Smart Price Pilot (OSPP), and the Energy Smart Pricing Plan (ESPP), and, although they both demonstrated to a limited extent that people do respond to price signals, their results also reveal that why people respond in the way they do is a long way from being understood. The OSPP, for example, showed very mixed results, with some critical days



achieving a large reduction in peak demand, whilst others saw either no response or even an increase in peak demand. Whilst admittedly these results are from a relatively modest-sized project, their variability is nonetheless a concern, and highlights the importance of trying to understand why they were like that. For example, why did customer response reduce as the project progressed? Furthermore, although participants felt that the price differential between peak and non-peak times was large enough for them to change their behaviour, those on the critical peak tariffs also felt that they had already reduced their consumption to the bare minimum, and that no more shifting was possible. Whilst these participants achieved a not insignificant peak reduction of between 17.5-25.4%, this reveals that there is a considerable challenge ahead if customers are to be convinced to reduce their peak demand any further.

The results from the ESPP emphasised the fact that customer response can vary in time – consecutive high price notifications produced diminishing responses. Evidently, people got increasingly fed up with having to curtail their demand, and became less willing to respond. This may not be a problem when there are only a few critical peak days per year, but what if customers are required to respond more frequently than this? Fundamentally, we do not know how and why people respond to price signals in the way they do. Without this knowledge, we should be wary of assuming that people will respond to price signals in a way that will enable a low-carbon power system.

### **The potential interaction between demand response and microgeneration**

Only one of the demand response projects reviewed here (Gridwise) appeared to consider the interaction between demand and local generation, yet this would seem to be a useful subject to explore and one that has received relatively little attention from the demand response community so far. It is possible that this type of interaction has not been explored because of historically low penetration levels of microgeneration, indeed the generators that participated in the Gridwise project were in fact relatively large (175 and 600kW) back-up diesel generators. Nonetheless, microgeneration has been proven to have a catalysing effect on consumers who have it installed (The Hub Research Consultants 2005) – one that could well be used in order to encourage demand response actions. For example, the simple addition of a red light that turned on when a household was exporting power to the grid worked as a very powerful signal for the

householders to take advantage of their ‘home-grown’ energy. The converse was also true, when the red light was off, they were incentivised to reduce their consumption. Whilst it would be perhaps unwise to say that, because of these findings, every consumer should become a *prosumer*, they nonetheless highlight the potential that microgeneration could have for securing demand response. A possible extension of this idea would be to include information about local microgenerators on in-home displays in the surrounding neighbourhood – people might be more inclined to shift their consumption provided they knew that the energy they consumed was being generated ‘locally’.

### **Do consumers act like economic agents?**

It is clear that demand response design is concerned with enabling consumers to participate more efficiently in the wholesale electricity market, either by providing them with appropriate price signals, or through incentives to install automated load control devices that can participate on their behalf. The task it seems is to turn consumers into better economic actors, such that their consumption is more accurately accounted for by its true, market cost. This reflects an important assumption within demand response design – that consumers are rational, independent, utility-maximisers.

Yet it is not at all clear that this is actually how people act and behave within the confines of their home. For example, the above case-studies help to reveal one of the key aspects in which this assumption might be off the mark: consumers are seemingly more risk averse than might be expected if they acted like perfect economic actors. In the Ripple Control system, the uncertainty surrounding the timing of peak periods was an unwelcome inconvenience to some participants. The successful uptake of the LIPAedge project was due in part to the fact that customers could override curtailment requests – and not be penalised for doing so given the lack of an on-peak tariff. Indeed, both the OSPP and Gridwise project imposed little or no risk on their participants, as any losses they incurred were compensated by ‘welcome’ payments for participating in the projects. Arguably, the ESPP project was the only one where customers took onboard real risks, and indeed this proved to be a considerable barrier to recruitment in the project. If consumers are so apparently risk-averse, then it may prove to be a considerable challenge for dynamic pricing tariffs to gain widespread acceptance within deregulated retail markets.

## CONCLUSION

The evidence presented here therefore indicates that people do respond to prices, but in a limited and complex manner. The results of these and other demand response projects demonstrate that peak demand can be reduced using automation and pricing signals, however care must be taken when assuming that consumers will respond to prices in a manner that will allow significant penetrations of wind power to come on-line. We can say tentatively that people tend to reduce their peak demand consumption when requested to do so, but so far this has only been tested when the peak period is either a regular, reliable occurrence, or when it is a much less regular event, in response to system emergencies. It is not clear how these findings are applicable to a low-carbon, wind-dominated future, where the challenge might be the need to shift peak demand according to unpredictable lulls and gluts of wind power. This paper finds that much more research is needed into the human aspects of demand response, and in particular on why people do (or do not) respond to price signals, as well as the side-effects of automation, before it will be valid to assume that these mechanisms alone will be sufficient to address this challenge.

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## REFERENCES

- COMMITTEE ON CLIMATE CHANGE, 2009. *Meeting Carbon Budgets - the need for a step change*. London, UK: .
- CYGNET SOLUTIONS, 2010-last update, Case study: Radio Teleswitching System. Available: <http://cygnets.co.uk/casestudies/rts> [02/16, 2011].
- DEPARTMENT FOR ENERGY AND CLIMATE CHANGE, 2010a. *2050 Pathways Analysis*. London, UK: .
- DEPARTMENT FOR ENERGY AND CLIMATE CHANGE, 2010b. *Energy consumption in the United Kingdom: Domestic Data Tables*. London, UK: .
- DEPARTMENT FOR ENERGY AND CLIMATE CHANGE, 2009. *Middle Layer Super Output Area (MLSOA) domestic*

*electricity estimates 2008: Great Britain*. London, UK: DECC.

- EUROPEAN COMMISSION, 28 Jan 2010, 2010-last update, Climate change: European Union notifies EU emission reduction targets following Copenhagen Accord [Homepage of Europa], [Online]. Available: <http://europa.eu/rapid/pressReleasesAction.do?reference=IP/10/97&format=HTML&aged=0&language=EN&guiLanguage=en> [27 Oct 2010, 2010].
- FRERIS, L. and INFIELD, D., 2008. *Renewable Energy in Power Systems*. 1 edn. Chichester, UK: John Wiley & Sons.
- HAMMERSTROM, D.J., 2007a. *Pacific Northwest GridWise™ Testbed Demonstration Projects: Part II. Grid Friendly Appliance Project*. Springfield, VA: National Technical Information Service, U.S. Department of Commerce.
- HAMMERSTROM, D.J., 2007b. *Pacific Northwest GridWise™ Testbed Demonstration Projects: Part I. Olympic Peninsula Project*. Springfield, VA: National Technical Information Service, U.S. Department of Commerce.
- KIRBY, B.J., 2003. *Spinning reserve provided from Responsive Loads*. Springfield, VA: National Technical Information Service, U.S. Department of Commerce.
- LONG ISLAND POWER AUTHORITY, 2001-last update, LIPA Edge, Cutting EDGE Technology: Program Details. Available: [http://www.lipaedge.com/program\\_details.asp](http://www.lipaedge.com/program_details.asp) [15th April 2010, 2010].
- MCCARTNEY, A.I., 1993. Load management using radio teleswitches within NIE. *Power Engineering Journal*, 7(4), pp. 163-169.
- NATIONAL GRID, 2010. *National Electricity System Seven Year Statement*.
- NEUBERG, A., 2009. Ripple control in the Czech Republic and Demand Side Management, 20<sup>th</sup> International Conference on Electricity Distribution, 8-11 June 2009 2009, CIRED, pp. 0515.

- NØRREGAARD, K., ØSTERGAARD, J., BACH, P.F., LIND, M., SØRENSEN, P., TENNBAKK, B., TOGEBY, M. and ACKERMANN, T., 2009. *EcoGrid.dk Phase I Summary Report: Steps towards a Danish Power System with 50 % Wind Energy*. Århus: Teknologisk Institut.
- OFGEM, 2010. *Demand Side Response: A Discussion Paper*. 82/10. London, UK: Ofgem.
- SCOTTISH POWER DISTRIBUTION, 2010. *Low Carbon Networks Fund: Demand Side Management of Electric Storage Heating*. London, UK: Ofgem.
- STAR, A., EVENS, A., ISAACSON, M. and KOTEWA, L., 2008. Making Waves in the Heartland: How Illinois' Experience with Residential Real-Time Pricing Can Be a National Model, *Summer Study on Energy Efficiency in Buildings*, 2008, American Council for an Energy-Efficient Economy.
- STAR, A., ISAACSON, M. and KOTEWA, L., 2010. *Evaluating Residential Real-Time Pricing: Connecting Customer Response to Energy Market Impacts*. Chicago, IL.: CNT Energy.
- STRAPP, J., KING, C. and TALBOTT, S., 2007. *Ontario Energy Board Smart Price Pilot Final Report: Prepared by IBM Global Business Services and eMeter Strategic Consulting for the Ontario Energy Board*. Ontario, Canada: OEB.
- STRBAC, G., 2008. Demand side management: Benefits and challenges. *Energy Policy*, **36**(12), pp. 4419-4426.
- SUMMIT BLUE CONSULTING, 2007. *Evaluation of the 2006 Energy-Smart Pricing Plan: Final Report*. Chicago, Illinois: CNT Energy.
- THE HUB RESEARCH CONSULTANTS, 2005. *Seeing the light: the impact of micro-generation on the way we use energy*. London, UK: Sustainable Consumption Roundtable.
- UK GOVERNMENT, 2008. *Climate Change Act 2008*. London, UK: .
- WILDI, T., 2000. *Electrical Machines, Drives, and Power Systems*. 4 edn. Columbus, Ohio: Prentice Hall.
- WOOLNER, L. and HANNON, T., 1996. Demand side management-latest developments in tele-technology, *Metering and Tariffs for Energy Supply, Eighth International Conference on (Conf. Publ. No. 426)*, 1996, , pp. 20-24.