EXPERIMENTAL VALIDATION OF RESIDENTIAL CONSUMER RESPONSIVENESS TO DYNAMIC TIME-OF-USE PRICING

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ABSTRACT

This paper describes the first analysis from the Low Carbon London (LCL), residential dynamic time-of-use (dToU) pricing trial that took place in the London area during 2013. High price induced peak reductions for network constraint management are investigated alongside the temporal availability of demand response for supply balancing. By examining both these use cases we identify potential conflicts between network and system objectives. Demand response results are stratified by a ranking metric for engagement with the dToU tariff as well as household occupancy and socio-economic classification.

INTRODUCTION

About the programme

The Low Carbon London (LCL) programme is a technology demonstrator financed by GB electricity consumers via the Low Carbon Network Fund (LCNF), administered by the Office of Gas and Electricity Markets (Ofgem). The programme was commissioned to demonstrate and gather performance data on a number of innovative "smart grid" technologies, of which this residential sector demand response trial was one. The trial simultaneously investigated consumer responsiveness [1] and attitudes [2] towards the experimental dynamic pricing tariff. Key partners in the design and implementation of this trial included UK Power Networks, the London distribution network operator (DNO) and lead programme partner; Imperial College London for trial planning, analysis and knowledge dissemination; EDF Energy, retail energy supplier and tariff implementer; Siemens for the information and communication technology (ICT) framework; and Logica for the smart metering head-end.

Motivation

To meet decarbonisation targets, approximately 20% of GB electricity demand will be met by renewable generation in 2020 [3], while electricity generation is expected to be mostly decarbonised by 2030 [4]. Furthermore, this may be accompanied by the electrification of segments of heat and transport sectors. This development will pose two major challenges [5]:

(a) Significant penetration of intermittent wind power and increased contribution from less flexible low carbon generation may greatly reduce the efficiency of the demand-supply balancing task if delivered by generation, as at present. This will significantly limit the ability of the system to accommodate low carbon generation, leading to significant increase in operating costs and carbon emissions. Hence, enabling the demand side of the electricity system to follow the supply side will bring significant savings.

(b) Load growth and integration of low carbon demand technologies, such as electric vehicles and heat pumps, will stress the electricity distribution network infrastructure, which will necessitate significant reinforcement investment. Therefore, reducing peak demand through demand response could postpone or displace network investment and facilitate a cost effective transition to a lower carbon future.

This trial investigates the potential dToU tariffs to deliver residential demand response to the Supplier, where it may contribute to system balancing through Supply Following (SF) actions, enhancing the ability of the system to integrate low carbon generation, and to the DNO, where it may be used for network Constraint Management (CM), displacing or deferring network reinforcement costs. These two are examined here in unison so that potential conflicts and synergies between the two may be better observed.

With the UK government's plan to roll-out smart meters by 2020, there exists the opportunity for consumers to make significant savings on their energy bills while supporting a cost effective transition to a low carbon future.

Related studies

Most relevant to this trial were results pertaining to the testing of time-of-use (ToU) and critical peak pricing (CPP) tariffs. Considering both context and scope, the most closely related trials to LCL were those of the Energy Demand Research Project (EDRP) [6] and the Ireland Electricity Smart Metering Trials (IESMT) [7]. EDRP results showed an approximate 4% reduction in weekday peak energy consumption for consumers with in-home displays – though significance was low due to the number (170) of participants. In contrast, IEMST results showed a 7-12% reduction in peak demand with participants numbering nearly three thousand. Results from North American trials show similarly large variations. In general, the literature indicates that economic incentives are effective in changing consumer behaviour [8]. Though results have been highly variable, it is commonly observed that the effect of such tariffs on total energy consumption is small compared to the effect on peak power demand.

Dynamic pricing in the residential sector is rapidly developing with multiple smart meter rollouts and demonstrator programmes on-going at time of writing [9]. EcoGrid [10], with some 2000 residential consumers participating in a dynamic pricing trial including integrated smart appliances, is perhaps the most closely related of the on-going EU projects.

TRIAL DESIGN

Recruitment: 5,533 households with smart meters were recruited onto the trial from the London Power Networks (LPN) area. All households agreed to have their half-hourly consumption data analysed as part the LCL project, and a subset of 1,119 households additionally signed up to receive a dToU tariff. At the end of the trial, valid data for the 2013 calendar year was available for 922 households on the dToU tariff and 3,437 households on the non-Time-Of-Use (nonToU) tariff.

Tariff: The dToU tariff, implemented by EDF Energy, was delivered under the product name "Economy Alert". It constituted three different price points, deliberately chosen to have a strong high to low price ratio, though still designed so that an average consumer's bill would be the same as on the nonToU group's flat rate tariff if their consumption profile remained the same. The values of the price points were; for high price, 67.20 pence/kWh; for default price, 11.76 pence/kWh; and for low price, 3.99 pence/kWh. Consumers in the nonToU group were given a flat rate tariff of 14.228 pence/kWh.

The middle price point was the default position with the high and low price points being used to generate the demand response events. There were two distinct types of event:

Constraint Management (CM) events: Designed to measure the potential for dTOU-mediated demand response to relieve distribution network constraints, and thus defer costly network expansion and increasing asset utilisation. The events targeted peak demand periods according to season and time-of-day, as identified using Elexon1 Profile Class 1 data. In order to incentivise the greatest possible demand reduction during the peak period, a high price point during peak hours was combined with a low price on either side for the remaining duration of that trial day. Events targeting the same daily peak on consecutive days were also trialled.

Supply Following (SF) events: Designed to scan the response of households to simple high or low price signals at different times of day and of varying duration. The objective of these events was to quantify the potential of dTOU-mediated demand response to assist in energy balancing. In order to span the range of variable output characteristics of renewable generation, such as wind power, a diverse set of events were trialled. Individual events consisted of single price changes, either high or low, over a range of event durations, arranged in time so as to systematically sweep across all times of day. Each event type was repeated 3 times and distributed randomly throughout the trial year of 2013. This design enabled the measurement of the participants' willingness to engage in DSR at different times in the day and year, and for different event durations.

Demand Response (DR): Defined as the change in demand induced by a price event. Its calculation requires a comparison of the observed demand with a hypothetical baseline demand for if the event had not occurred. A linear regression model was used to compute a per-household baseline demand based on that household's relation to the nonToU group. Dummy variables were included to modulate for temporal factors; one binary variable for each hour of the week and an index variable to account for gradual load growth. By coupling the baseline to the behaviour of the nonToU group, it correctly accounts for non-standard days (e.g. bank holidays) and special events. While each baseline demand model reflects only the average behaviour of that household, random deviations from the model will tend to cancel in aggregate operations (e.g. the mean demand of a group of households). This approach therefore couples the benefits of a mean response model with the ability to arbitrarily stratify household groupings.

KEY FINDINGS

Consumer engagement

Consumers were incentivised to change their electricity consumption through the price changes built into the dToU tariff. This tariff was designed to result in the same revenue as the nonToU flat rate tariff, for the average consumer who did not react to the price changes over the year. Therefore, a reduction in the annual bill on the dToU tariff relative to the equivalent consumption on the flat rate tariff is a first indicator of consumer engagement. Using this measure, over 95% of households saved money during the trial year – significantly greater than the 50% that would be expected if consumers had not engaged at all.

Although the observed decrease in annual bills is a good indicator of overall engagement, it does not necessary extend to individual households. For example, consumers who are often away during the evening are likely to have missed the CM-type evening peak trials, resulting in lower average bills. To rank the engagement of individual households with the tariff, a non-parametric measure of relative responsiveness to dToU signals was developed (publication in preparation). This determines the likelihood that the realised annual bill came about by chance, if the household had paid no attention to the dTOU signal. If this likelihood is very low, it is assumed that the household has actively responded to the signal, whereas a high likelihood is consistent with a lack of engagement. The likelihood measures were used to rank all households according to their perceived responsiveness to dTOU signals.

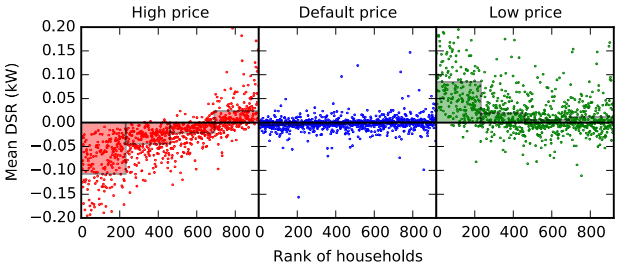

Figure 1: Household performance rank against measured DR, by price point.

Figure 1 demonstrates the relation between the responsiveness ranking and the mean observed demand response across all trials. The panels depict the response to high (left), mid (centre) and low (right) price signals respectively. Each dot represents a single household with its responsiveness ranking on a range of 1 to 922 shown on the x-axis. The estimated demand response is computed by averaging the deviations from the estimated baseline consumption over the period in which the relevant price (high/mid/low) is applied.

As expected, highly engaged households (low rank index) tend to decrease their consumption in response to high price signals and decrease their consumption in response to low price signals, and the magnitude of the response generally decreases with increasing rank index. The figure also illustrates an interesting feature of the responsiveness ranking method: the highest ranked households are not necessarily the ones with the highest absolute change in demand in response to price signals. This is because the method does not quantify directly the magnitude of the response to price signals, but its consistency and the degree to which it can be ascribed to chance. This means households with limited means of demand response may still rank highly if fluctuations in the consumption are clearly linked to the dTOU signal.

The ranking of households according to their responsiveness also plays a key role in the extrapolation of results. The highly ranked households are assumed to be indicative of future consumers that are increasingly responding to dTOU signals, either manually or mediated by home automation devices and services. To capture this, households were classified into four groups according to their responsiveness ranking. Throughout this paper results are, where possible, reported stratified by engagement ranking. As business-as-usual (BAU) use of a dToU tariff would likely see customers gaining experience, understanding and assistive technology (such as smart appliances), it is plausible that the more engaged households in this trial are indicative of the future BAU responsiveness potential.

Reduction of peak demand

The CM events were consistently able to reduce peak demand levels. Figure 2 shows a CM event designed to achieve weekday evening peak reduction over two consecutive days. The background colour indicates the active price point and the dark line shows the observed demand levels. The inferred changes in demand compared to the baseline are drawn in red (increase) and blue (decrease). The lighter curve shows the same results restricted to the 25% of best responding households.

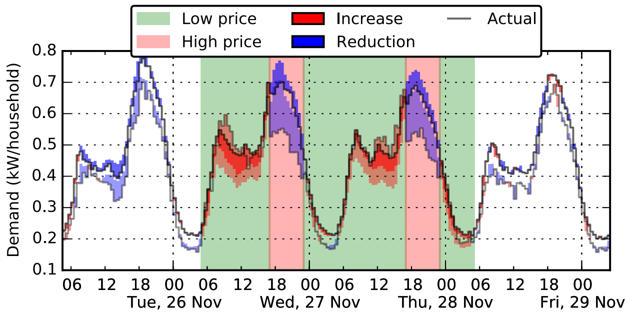

Figure 2: A CM event showing evening peak reduction over two consecutive weekdays. The lighter shaded Increase, Reduction and Actual indicate the response from the most engaged 25% of households.

A sizeable reduction in demand can be seen during the high price periods. The participating households reduced their average peak demand level by approximately 9%, with the highest performing households showing a significantly larger reduction of 20%. Furthermore, the reduction in peak power consumption persisted across both event days. The reduction in load during high price periods was accompanied by an increase in load during the adjacent low price periods. These features – peak reduction, persistence and load shifting – were consistently observed for CM events, with peak reduction values between 5% and 10% on average.

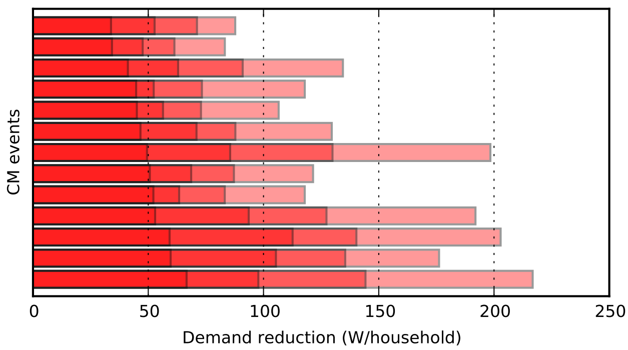

Figure 3: Mean change in demand over the high price period of the CM events. Bars, from lighter to darker shading, represent the average for subgroups of the most engaged 25%, 50%, 75% and 100% of responders.

Figure 3 depicts the observed changes in consumption during high price periods, for each of the CM-type events in the trial. The results demonstrate a robust reduction in average load of approximately 50 W/household, which more than doubled to a range of 80-220 W/household for the subpopulation of the 25% most responsive households. Such demand reductions may be considered material for future network planning.

Demand response is time dependent

Targeted high and low price events were used to establish the potential for consumers to respond to dToU signals at different times of the day and throughout the year. As expected, households responded to high price signals with decreases in consumption levels that were much larger during the colder and darker winter months than in the peak of summer. Curiously, the ability of households to *increase* power consumption was only very slightly affected by the time of year. During the summer months in particular this led to an asymmetric response to high and low price signals.

Figure 4 breaks down the average change in demand by half-hourly settlement block, for both high (red) and low (green) price events. The bars with the darkest shade represent the mean response of all trial participants, and the progressively lighter bars the results obtained by analysing the subpopulations of 75%, 50% and 25% best ranked responders.

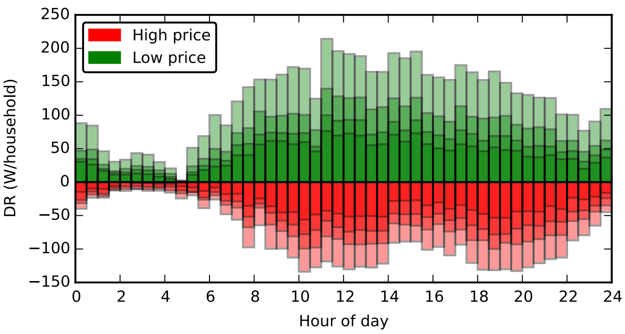

Figure 4: Full year mean DSR by hour-of-day for SF events only. Bars, from lighter to darker shading, represent the average for subgroups of the most engaged 25%, 50%, 75% and 100% of responders.

The demand *reduction* potential (in red) is seen to reach its maximum magnitude around the morning and evening peaks (on weekdays). The most responsive quarter of households achieved a mean demand reduction over 120 W/household during these periods, compared to 50 W/household for the average household.

The ability to *increase* demand levels was fairly constant during the waking hours of the day, at a level of 50 W/household across all households and exceeding 150 W/household for the most responsive households. During the night-time even the best responders do not achieve an increase of 50 W/household. This suggests an ability of households to assist in supply demand balancing, but this potential is currently limited to waking hours and is significantly larger during winter months. A more consistent response may be possible using autonomously responding appliances.

The general pattern of response magnitude seen in Figure 4 suggests a relationship with the level of demand at the time of the price event. This is corroborated by correlation coefficients of -0.75 and 0.47 for all response measurements at high and low price point respectively, against the per-household baseline demand. This correlation between demand reduction potential and absolute demand levels is a positive finding for the Constraint Management use case, as the reduction potential during peak demand periods will be higher than suggested by average response numbers.

Potential conflicts between network and system objectives

The trials specifically addressed the use cases of Constraint Management (CM) and Supply Following (SF). The CM use case supports the operation and planning of the distribution network, whereas the SF use case supports supply-demand balancing at the system level. As the availability of responsive demand increases, these two objectives may lead to conflicts that are not present in the current operating practice. For example, an abundance of available wind power or the availability of large amounts of inflexible nuclear plant during low load conditions may result in very low electricity prices. From the system perspective it would be beneficial to use dToU pricing to incentivise consumers to increase their consumption levels. However, doing so might cause unanticipated stress on the distribution network.

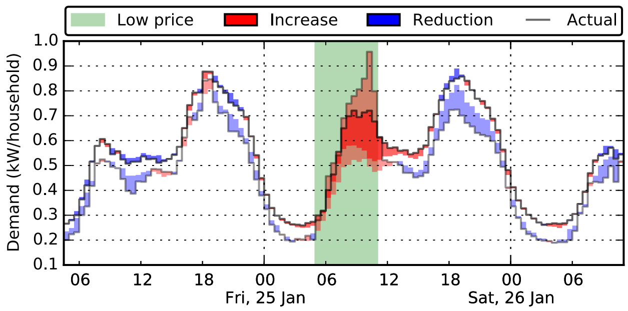

Figure 5: Demand increase in response to a low price signal. The lighter shaded Increase, Reduction and Actual indicate the response from the most engaged 25% of households.

That such a situation is not hypothetical is borne out by the low price event shown in Figure 5, where the low price was offered between 5am and 11am on a Friday morning. In response to this signal, households increased their average power consumption from just under 0.6 kW to just over 0.7 kW. However, the subpopulation of 25% most responsive households, which may be indicative of future participation levels, demonstrate a much larger response. Their morning consumption levels nearly double relative to the baseline – a change that is sufficient to shift the daily consumption peak from the evening to the morning. If unanticipated and unmanaged, such an event might pose severe difficulties for the DNO.

Socio-economic factors hardly affect response magnitude

The responses of the targeted SF and CM events were analysed against two principal parameters that are known to be strong indicators of energy consumption: household occupancy; 1, 2 and 3+ (three or more occupants); and a socio-economic classifier based on the Acorn group definitions [11], defined as: Affluent {A, B, C, D, E}, Comfortable {F, G, H, I, J}, and Adversity {K, L, M, N, O, P, Q}. The three socio-economic groups can be interpreted as a rough indicator of wealth.

Figure 6 shows the average demand response for these classes averaged over all SF events (shown here because, in contrast to CM events, their randomised distribution and equal counts of high and low price events gives a more balanced indicator of group response). Perhaps surprisingly, the socio-economic class had little impact on the observed demand response for these single events, although results from CM events suggest that households in the Affluent class may respond more strongly to signals that specifically targeted peak hours.

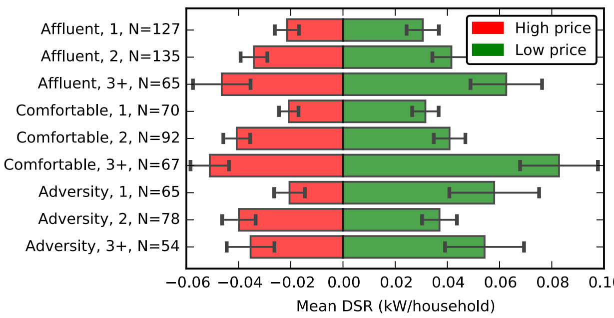

Figure 6: Mean DR by LCL Acorn and occupancy class for SF events only. Error bars depicting the standard error of the mean across households are included to indicate the significance of the results.

The measured response does depend strongly on occupancy levels, with larger households providing responses of larger magnitude. An apparent exception is formed by the larger (3+) Adversity households, which do not exhibit a significantly larger response than the lower occupancy households, although this finding is only marginally significant.

CONCLUSIONS

In this paper we describe the motivation, design and first results of the Low Carbon London programme's experimental dynamic-time-of-use (dToU) tariff for the residential sector. The following key findings were identified:

- Results show that over 95% of customers saved money relative to what they would have consumed on the standard flat rate tariff.
- To further explore the extent of customer engagement, we developed a non-parametric ranking metric. As business-as-usual (BAU) use of a dToU tariff would likely see customers gaining experience, understanding and assistive technology (such as smart appliances), we propose that the more engaged households in this trial may be indicative of the future BAU responsiveness potential.
- Over all constraint management (CM) events, households achieve an average reduction of 50 W/household. However, for each CM event, the average household response more than doubled when only the subpopulation of the 25% most engaged households was considered.
- Demand response was seen to be highly time dependant, with the greatest response occurring between 7am and midnight, consistent with expectations for manual responses to dynamic pricing.
- The pattern of response was also found to correlate with the magnitude of the demand at the time the price events occurred, with correlation coefficients of -0.75 and 0.47 for all response measurements at high and low price point respectively.
- Potential conflicts between network and system objectives were observed. Low price events were seen to have the potential to create peaks in demand that exceed the typical maximum of the day.
- Socio-economic factors were seen to have no significant effect on demand response.

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