ANALYSIS OF CUSTOMERS' PERFORMANCE IN INDUSTRIAL & COMMERCIAL DEMAND SIDE RESPONSE TRIALS

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ABSTRACT

Modern distribution networks face the challenges of growing demand and ageing assets. Demand Side Response (DSR) provided by Industrial and Commercial (I&C) customers is viewed as a means to help reduce risk of substations and feeders overloading and thus to defer network reinforcement. However, real world experience regarding the use of I&C DSR in distribution networks is currently limited, and experimental data from trials and case studies is sparse. The recently completed Low Carbon London project included I&C DSR trials aimed at understanding the potential for I&C DSR for distribution network constraint management. This paper presents the data obtained in the course of these trials and discusses in detail the process of data collection, selection, baseline construction, preparation for analysis and subsequent development of probabilistic response models. Additionally, a potential issue – the presence of a payback effect in customers responding with HVAC units – is observed and discussed.

INTRODUCTION

Modern distribution networks face the challenges of growing demand and ageing assets. Targeted load reduction using Demand-Side Response (DSR) is viewed as a means to help reduce risk of substations and feeders overloading and thus defer network reinforcement. Industrial and Commercial (I&C) DSR is particularly appealing due to the large potentially available capacity ($\sim10^2$ – 10^3 kW per site). However, in a distribution network context DSR becomes 'network-constrained': the ability of customer to meaningfully participate in DSR depends on that customer's location in the distribution network. The number of customers that are able to contribute may therefore be small, while their variety in size and type of business is large. In this scenario it is no longer sufficient to characterize the average performance of a DSR site, so that the full range of possible responses to a DSR event must be quantified.

This paper presents results of I&C DSR trials that have been performed as a part of the recently completed Low Carbon London (LCL) project, which was led by UK Power Networks and funded by the Great Britain regulator (Ofgem). The trials, performed with load aggregator partners KiWi and Flexitricity, provided valuable experience concerning the use of I&C DSR by a Distribution Network Operator (DNO) for distribution network constraint management. The LCL Learning Lab at Imperial College has compiled the insights gained from these trials in reports [1] and [2]. The work presented in [1] focused on the compliance of customers' performance to the contract, while material in [2] emphasised the reliability aspects of the observed performance (dependability).

This paper describes the analysis of the data obtained in the course of the trials, including detailed discussion of data collection, selection, baseline construction, preparation for analysis and development of probabilistic response models.

DESCRIPTION OF TRIALS

LCL I&C DSR trials were conducted in the same manner as currently exercised DSR programmes for system-wide services [3],[4]. Load aggregators (LA) submitted portfolios of customers combined into assets of fixed capacity to the Distribution Network Operator (DNO), which were then dispatched by the DNO at a predetermined day and time (usually with a 30 minute notice period). After the end of the DSR event participants' performance was compared to their respective baselines and rated in accordance with existing practice.

A wide range of customers were signed up for participation (including hotels, hospitals, department stores, office buildings), and 189 DSR events in total were generated during two stages of the trials. The first stage was carried out in summer 2013 (from June to August) with a total of 128 DSR events generated by 26 participants. The second stage was conducted in winter 2013/14 (from December to February) with a total of 61 response events spread across 9 participants, 7 of which also participated in the summer trials. The trial participants used a range of technologies to provide response. At a high level, these could be arranged into two categories, each with two sub-categories:

a) Generation-led DSR, able to start generating on demand
   a. On-site diesel generators
   b. CHP engines with a cyclic operating regime
b) Demand-led DSR, reducing site electricity consumption on demand
   a. HVAC installations
   b. Water pumping stations

Table 1 shows a breakdown of the sample of all 189 DSR events by season (summer/winter), response type (generation-led DSR/demand-led DSR) and type of equipment used:

Table 1: Event counts with breakdown by participant type. Number of sites indicated in brackets.

		Summer 2013	Winter 2013/2014
Generation-led DSR	Diesel generators (5)	25	21
	CHP plant (3)	11	9
Demand-led DSR	HVAC (15)	62	31
	Water pumping stations (5)	30	-
Total events		**128**	**61**

DATA SELECTION AND PREPARATION FOR ANALYSIS

Raw data collection and initial selection

In order to estimate and analyse the performance of customers participating in the I&C DSR trials, the following data was needed:

a) High-resolution meter readings for DSR-event days;
b) High-resolution historical data for baseline construction.

Raw data was provided to the LCL Learning Lab in the form of load profiles for all 28 participating sites, covering both summer and winter trials. Load profiles typically contained meter readings in 1-minute resolution. Two sites (10 DSR events in total) were available only in half hourly resolution, which is insufficient to properly capture 1-hour DSR events. Therefore, these were excluded from further analysis. Five additional events (two in summer and three in winter trials) were excluded based on the fact that load profiles for those days were absent from data provided. In addition, one of the water pumping stations was excluded due to the non-responsiveness across all six relevant events. Finally, one CHP unit (13 events across summer and winter trials) was excluded from further analysis because of an apparent variable measurement offset that introduced spikes in measurements and baselines. The remaining 155 DSR events were taken to the next step: baseline construction.

Baseline construction

For demand-led DSR the magnitude of the response of a given site and event cannot be measured directly. Rather, it must be inferred from the measured electricity consumption and the load *baseline*, an estimate of what trial participant's electricity consumption might have been in the absence of the DSR event [5]. The baseline takes the form of a reconstructed hypothetical load profile on the day of DSR event and it is used as a benchmark to quantify a participant's performance.

The meaning and importance of baselines along with advantages and disadvantages of various baselining methodologies were discussed in detail in a number of publications [5] [6]. The Symmetric high 5 of 10 (H5o10) method [5] was adopted for baseline construction in the cases where meter readings were provided at the site level. In the cases of generation-led DSR, where meter recordings were collected straight from the devices, the baseline was set at zero. The H5o10 method requires the availability of consumption measurements on 10 working days before the event. In order to enlarge the pool of available events for the probabilistic analysis, we opted to relax these strict requirements in two ways. When insufficient suitable days were available before the event, additional days were selected *after* the event date. Furthermore, when that was also insufficient, high 5-of-9 or high 4-of-8 were used as required.

In this way, baselines were constructed for 153 events. For the two remaining events, load profiles for non-event days were not available, precluding the construction of a baseline. One additional event was discarded due to data dropouts on days used for constructing the baseline. The breakdown of DSR events ultimately accepted for analysis in this chapter is given in Table 2:

Table 2: Events accepted for further analysis.

		Summer 2013	Winter 2013/2014
Generation-led DSR	Diesel generators (5)	23	18
	CHP plant (2)	3	3
Demand-led DSR	HVAC (13)	50	31
	Water pumping stations (4)	24	-
Total events		**100**	**52**

We note that the H5o10 method is computed using only consumption data. When additional data is available, more accurate baselines may be computed. An example involving physical modeling of an HVAC system is described in [1]. This method uses parameters obtained from building characteristics and the Building Management System (BMS) of a customer, as well as weather data. These parameters were combined in the model with DSR event characteristics, such as the contracted response level of a participant, day of event, notification time and proposed event duration.

Figure 1 shows simulation results, where a baseline constructed using the physical modelling method is compared to the load profile and H5o10 baseline. It is clearly seen that the former tracks the realized load profile more closely than the latter.

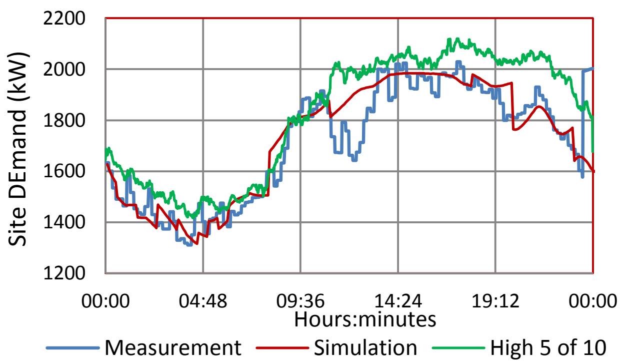

Figure 1. Baseline constructed using physical modelling of HVAC system in a building on the day of the DSR event.

ANALYSIS AND FINDINGS

Estimation of trial participants' performance

The trial participants varied significantly in the magnitudes of their electricity consumption and response. Furthermore, events of different duration occurred. In order to focus on the qualitative similarities and differences between responses, all events were normalised to a common scale, both in magnitude and duration. This established two common scales (one for response level and one for event duration) on which participants' performance can be compared, aggregated, averaged or be subjected to other mathematical operations, depending on analysis purposes.

Figure 2 shows the resulting traces for all events, categorised by DSR technology and summer/winter trials. Traces were discretised into 20 intervals each by local averaging. This provides a level of smoothing that aids visualisation and also reflects the fact that fluctuations on very short time scales do not necessarily constrain the network, due to the thermal mass of network assets. A few general observations can be made based on these traces.

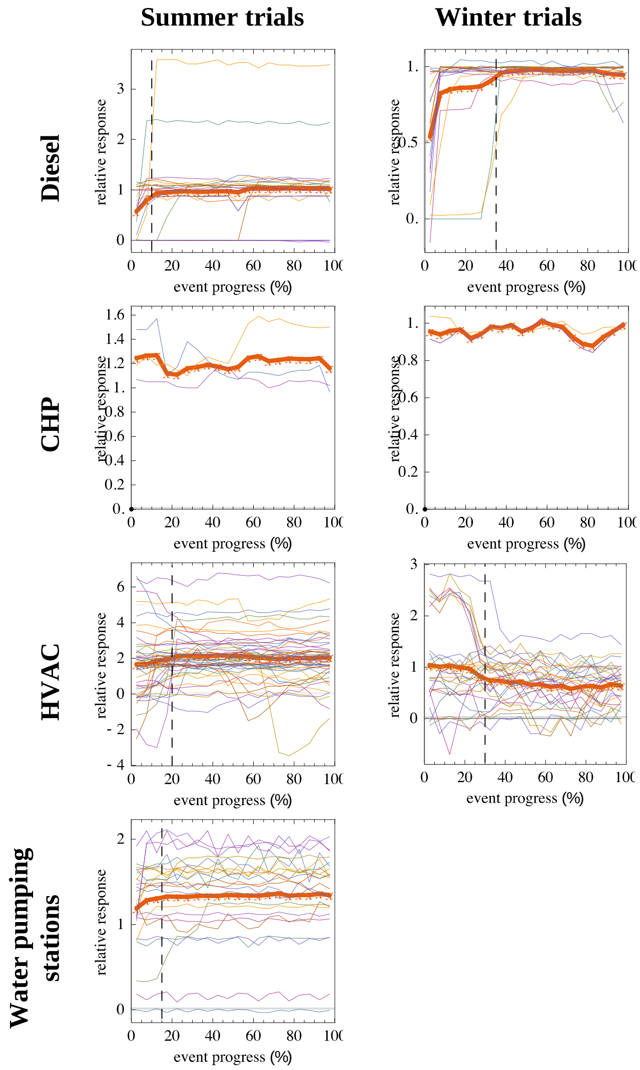

Figure 2. Event traces used for statistical analysis. Thick orange line indicates average response.

- Generation-led DSR (diesel and CHP) provides response values that are closest to the contracted amount (1.0 in this representation), consistent with their direct controllability. The clear exception is when units did not respond at all, which happened four times for the diesel sites during the summer trials.
- The response of demand-led DSR (HVAC and water pumping stations) is more variable, both in terms of average magnitude and the inter-event variation. The inter-event variation may be partially attributed to the fact that – in contrast to generation-led response – demand-led DSR is defined with respect to a non-zero, and therefore noisy, demand baseline.
- HVAC systems demonstrated much larger response magnitudes – and variability – in the summer trials than in the winter trials. This is consistent with the

larger dependence on air conditioning in the summer months, allowing for larger reductions.

- Initial transient behaviour was observed for many traces. This was often in the form of a late start of the response, but the HVAC winter trials also contained initial overshoots, where sites overdelivered before returning to a nominal power reduction level. After this initial ramp, most event traces demonstrate a relatively stable response. The vertical lines in
- Figure 2 indicate the visually identified transition between these two regimes for each DSR type and trial set.

Probabilistic models

There are a number of ways to interpret customers' performance. One of them is compliance with the contract; another is the dependability of I&C DSR if it is used for load reduction by a DNO. These two influence data treatment significantly and have serious implications on subsequent analysis. Both will be discussed below.

It was shown in the previous section that generation-led and demand-led responses have fundamentally different response characteristics, and further differences occurred between summer and winter trials. The typology with seven different *event classes* as introduced in Table 1 and Figure 2 will be used throughout this section to illustrate the resulting differences on aggregate site performance.

As a first step the performance for each site and event was quantified by averaging the site's relative performance over the stable response duration of the event (to the right of the dashed lines on the diagrams in Figure 2), as defined per event class. This resulted in a set of numbers for each event class. Those numbers (across relevant sites and events) were assumed to be independent realisations of an underlying probability distribution for each event class. The observations were then used to define an empirical probability distribution in the form of a cumulative distribution function (CDF); each outcome was considered an equally likely outcome of a random response. A guide to their interpretation is shown below in Figure 3, with the contractual performance (value 1) indicated by a green dotted line.

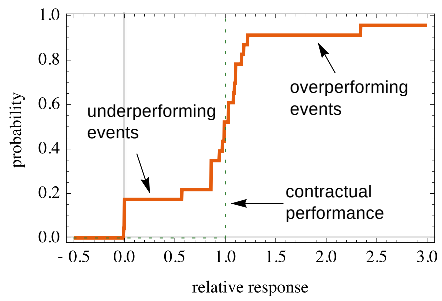

Figure 3. The interpretation of event class CDF's.

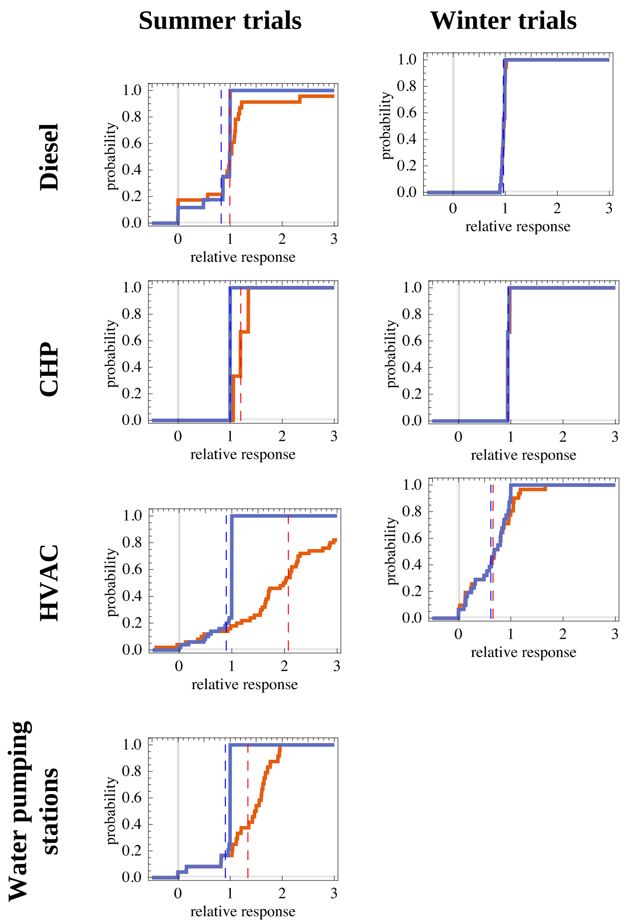

Figure 4. Empirical CDFs with and without clipping.

The resulting CDFs are shown in the Figure 4. Their values for a response value *r* indicate the probability that a response of *r or less than r* is realised. By definition, the curves start at 0 on the left and end at 1 on the right.
The statistical analysis described above was performed in two variations. First, the observed responses were clipped to the interval [0,1] before averaging (blue lines). This reflects the 'contractual' point of view, where a load reduction in excess of the contracted amount is ignored. In this case, the measured average response always lies within the range [0,1] and can be considered a measure of compliance. The second analysis approach (red lines) does not perform this clipping. Because this measures the *actual* load reduction on the network this is arguably the perspective that is more suitable to DNO constraint management. The mean response values are also depicted in Figure 4, using dashed vertical lines (blue for clipped, red for unclipped). It is clear that the use of clipping in the analysis has very significant effects on the inferred probabilistic model. The difference is especially pronounced for the HVAC units in summer, where responses up to 6 times the contracted value have been observed, and the mean response was more than twice the contracted value.

It is worth pointing out that the number of independent sites involved in the trials was limited, as was the number of trial events, so that statistical fluctuations have a substantial impact on reported results. This is especially true for the CHP curves, which are based on three events for a single site each. Furthermore, involvement in the trials has led to substantial opportunities for learning, the effects of which cannot be disambiguated from seasonal effects between summer and winter trials. For these reasons, the range of results from the quantitative analysis should be taken as an indicative of the type and variability of performance that might be encountered.

Payback

It has been noted that demand-led DSR may take the form of demand shifting, where the initial demand reduction is followed by a payback phase in which the load increases with respect to the baseline. If DSR is used for constraint management by the DNO, the payback effect may result in postponing rather than resolving the network constraint. Figure 5 shows payback traces for HVAC groups (summer and winter respectively), constructed in a similar manner to the response traces in Figure 2.

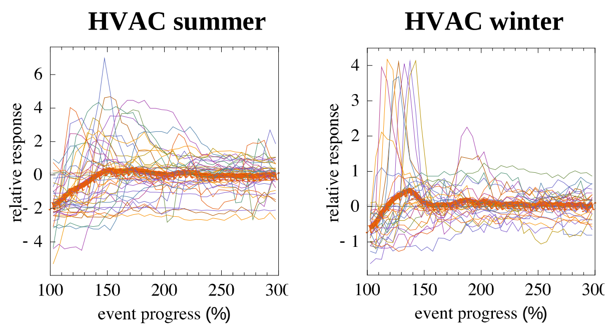

Figure 5. Payback effect seen in after-event response traces. Thick orange lines indicate the average response.

In the LCL I&C DSR trials, payback peaks have been observed with a magnitude up to 8 times the contracted load reduction. The peak magnitude was found to be highly variable, but generally characteristic for the site. Based on this experience, it would seem reasonable for the DNO and aggregator to profile a site's 'payback signature' as part of the sign-up process, and perhaps subject it to contractual limitations.

CONCLUSIONS AND FURTHER WORK

This paper has presented the observed responses of Industrial and Commercial sites that participated in the Low Carbon London I&C DSR trials. A step-by-step description was given of the data analysis, resulting in probabilistic response models for seven event classes that are characterised by site technology and season. Furthermore, participants' performance was discussed from the point of view of interest to a DNO for network constraint management. In particular, the potential relevance of accounting for overperforming sites was demonstrated. Finally, the presence of payback effects in participants responding with HVAC units was observed and its implications for constraint management were discussed.

The Low Carbon London I&C DSR trials have produced valuable experience and data that will inform the future use of I&C DSR for distribution network constraint management. Probabilistic models such as those constructed in this paper may be used, for example, to analyse the aggregate performance of multiple sites for the assessment of I&C DSR reliability.

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