DNO Guide to Future Smart Management of Distribution Networks Summary Report

By UK Power Networks & Low Carbon London Learning Lab
London’s carbon reduction targets are only achievable if they have the smart electricity infrastructure to support them.

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SDRC compliance
This report is a updated version of the report submitted to Ofgem that was a contracted deliverable from the Low Carbon London project as set out in the Successful Delivery Reward Criteria (SDRC) section “Final Analysis”. This report contains additional sections in the form of a foreword and chapter introductions to aid the reader in their progress through the document.
I am delighted to present the Summary Report for Low Carbon London; one of Britain’s largest smart grid trials.

UK Power Networks is a strong champion of innovation as we believe this will help provide answers to the challenges that Britain’s move to a low carbon economy will pose to the way we build, operate and maintain our electricity distribution networks to suit your needs. Low Carbon London has been the flagship innovation project for our London network for the past four years.

London has targets for a 60% reduction in carbon emissions compared to 1990 levels by 2025 and 25% of energy from decentralised sources by 2025. Highly developed plans to meet these targets include distributed generation, co-generation of heat and power, electric vehicles, heat pumps and other low carbon technologies. Together these are expected to add substantially to demands on the electricity networks.

As operator of the capital’s electricity network and with the future energy demands of a sustainable city in mind, we used London’s network as a test bed for our Low Carbon London project. The project has generated a wealth of knowledge from cutting-edge trials which involved thousands of Londoners. These insights are captured across a total of 27 reports, of which this is the Summary Report.

This £28.3million project was funded by customers through Ofgem’s Low Carbon Networks Fund and by UK Power Networks. We are confident that the benefits to all customers will far exceed this figure. Demand Side Response, which was trialled on Low Carbon London, is now on course to save customers £43million on the cost of delivering their electricity over the next eight years.

I trust that within these reports you will gain an insight into how we are preparing ourselves for the low carbon future and the ‘energy trilemma’ of delivering low carbon, affordable and secure power supplies.

Finally I would like to thank our 11 dedicated project partners, without whom we could not have delivered this comprehensive smart grid trial.

Basil Scarsella
Chief Executive Officer

Foreword
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Who are UK Power Networks?

We are the Distribution Network Operator (DNO) for London, the East of England and the South East of England. This means that we own and maintain the electricity cables, lines and other electrical infrastructure across these areas for distributing electricity to homes and businesses. We are also responsible for making sure that your lights stay on. We do this by monitoring and controlling the distribution of electricity 24 hours a day, maintaining and upgrading electrical infrastructure to keep it highly reliable, and by connecting new electricity cables and lines driven by your needs.

In a world where our sources of electricity are changing rapidly, driven by the need to reduce carbon emissions, reduce our dependency on imported fuels and keep electricity bills affordable, the way we carry out our role is also changing dramatically.

UK Power Networks is a strong believer that innovation will help us adapt to these changes in a timely and cost efficient manner. Ofgem, our Regulator, also recognised this several years ago and in 2010 established the Low Carbon Networks (LCN) Fund. This £500m fund allows DNOs to try out new technology, operating and commercial arrangements. The aim of the fund is for DNOs to understand how the move to a low carbon economy can be facilitated by the distribution networks. The fund has been available for 5 years from 2010 and major projects have been awarded funding through an annual competitive process.

We are convinced that the investment Ofgem is encouraging through the LCN Fund will benefit all customers, many times over, both now and in years to come. One example of this is our Low Carbon London project, where we have trialled solutions which have led us to identify savings of £43m to pass on to our customers.

We have shown a great deal of commitment to the LCN Fund. We have submitted bids for major innovation project funding via the competitive process every year since its inception, and we have been successful every time. The result is that we have a portfolio of six major innovation projects, each one with a duration of 3-4 years, covering a wide range of innovation topics which address the major challenges facing the DNOs in the transition to a low carbon economy. In addition to Low Carbon London, we have major innovation projects to trial the flexible management of renewable generation through faster and cheaper connections to the distribution network (Flexible Plug and Play), trials of large scale energy storage (Smarter Network Storage), trials to engage vulnerable customers on energy efficiency activities (Energywise), implementation of power electronics to create more flexible local distribution networks (Flexible Urban Networks – Low Voltage), and active management of variable power flows on a 132kV network with a high density of intermittent generation (Kent Active System Management).

One of our commitments throughout these projects is to ensure that we share our learning for the benefit of the industry and our customers to ensure that the customers’ money invested in these projects delivers the maximum impact across Great Britain. We use a number of channels to ensure that we share our learning; from publishing papers, to presenting at conferences and the learning events that we host, to the detailed technical workshops that we run for our industry peers. We also ensure that we learn from our peers in the industry; for example in the case of our Low Carbon London project we have made sure that we derive learning from Northern Powergrid’s Customer Led Network Revolution project and we would encourage other stakeholders to do the same.

This approach ensures that together as a sector and with Ofgem’s continued support we will be ready to support the low carbon transition.
Smarter Network Storage
Start date: January 2013
End date: December 2016
Funding: £18.7m

FUN-LV
Start date: January 2014
End date: December 2016
Funding: £8.86m

Low Carbon London
Start date: January 2011
End date: December 2014
Funding: £28.3m

FPP
Start date: January 2012
End date: December 2014
Funding: £9.7m

Energywise (VCEE)
Start date: January 2014
End date: December 2017
Funding: £5.29m

KASM
Start date: January 2015
End date: December 2017
Funding: £3.85m

Funding = Low Carbon Networks Fund + UK Power Networks’ funding + Partner funding
Following the Climate Change Act 2008, and the associated commitment by the UK to reduce greenhouse gas emissions by 80% by 2050, the UK is poised for a significant transformation in how electricity is both consumed and generated. Distribution Network Operators (DNOs) will be required to adapt and invest more smartly to manage this new energy paradigm.

Low Carbon London (LCL) is a pioneering project that has trialled and demonstrated a broad range of smarter potential approaches to how distribution network operators may invest and operate in the future. By bringing together leading industry specialists, the project is a multi-party approach emulating what the 2020 or 2030 electricity supply chain (from System Operator to distribution network, distributed generation and supply) may look like.

To best demonstrate, test and quantify the impacts of the future low carbon distribution network, LCL conducted several trials which included:

- Monitoring Low Carbon Technologies (LCTs) for both power quality and network impact at scale;
- Implementing Smart Meters to understand their potential as both a network information point as well as the facilitator for future Time-of-Use (ToU) tariffs;
- Conducting Demand Side Response (DSR) and signing new commercial arrangements with Industrial & Commercial (I&C) customers;
- Testing demand flexibility for network Constraint Management (CM) and Supply Following (or “wind twinning”) by implementing a residential Dynamic ToU tariff;
- Analysing opportunities (including Smart Appliances) for energy efficiency;
- Monitoring Distributed Generation and validating opportunities for Active Network Management (ANM), and
- Developing new tools, and outlining planning, operational and investment practices.

Executive Summary
Due to the multi-faceted nature of the network, London has proved to be the ideal test bed for such a project. The city and Greater London area has the highest concentrations of electricity demand and CO₂ emissions in Great Britain, and the most demanding carbon reduction targets (60% reduction on 1990 levels by 2025). However, the trials and associated findings are designed in such a way as to be relevant and applicable to other urban networks across Great Britain, as well as being relevant to all major urban centres globally.

To provide clarity and ease of navigation through the LCL project findings, the suite of output reports have been categorised into themes. This enables readers to easily approach what might be an intimidating volume of information. The themes are:

- DSR and Distributed Generation (DG);
- The electrification of heat and transport; and
- Network planning and operation.

Taking all the findings into account, the project then considers the role of DNOs in a medium and long term, with the objective of defining the future Distribution System Operator. A DSO is typically agreed as being an operator with a more frequent or ‘active’ management of the network, often facilitated by commercial agreements with network users (whether I&C demand, generation or residential customers) and balancing these interventions alongside traditional capital investments. As such, the final reports present this as the fourth theme. The final reports address topics including planning, operational and systems changes required to deal with new residential customers smart meter information, alternative approaches for considering network resilience, investment options through the use of DSR and alternative regulatory approaches to ‘smart’ investments.

The project also considered the carbon impact of the future smart distribution grid. This looks at the possible flexibility provided by future LCT loads and new commercial arrangements such as DSR and dToU. In addition, the project has continuously monitored and recorded the impact of the projects trials in carbon terms. This extends to every intervention made by the project in issuing DSR events to I&C customers, every residential tariff price signal, every Electric Vehicle (EV) charging event and each Heat Pump (HP) running. Furthermore, these have been brought together in the final section of this report and assessed relative to the carbon and investment assumptions made at the outset of the LCL project.

Within each theme, there are numerous reports covering different trials and findings from the project. Throughout the body of this document you will find descriptions of the LCL reports and key findings as well as direction to which report may be of further interest. The complete set of reports is listed in the introduction section of this summary report.

**Demand Side Response and Distributed Generation**

LCL trialled and demonstrated DSR services from both I&C and residential customers. Residential customers, facilitated through smart meters installed by our project partner EDF Energy, were offered a first of a kind dynamic Time-of-Use (dToU) tariff, not previously trialled in Great Britain. Half hourly (HH) measurements, and in the future half hourly billing, available from smart meters allowed the project to offer a three tier price tariff to over 1,100 electricity customers. Publically this tariff was offered with the title ‘Economy Alert’.

The dToU tariff contained three different price bands, deliberately chosen to have a strong high to low price ratio, though still designed so that a consumer would be revenue neutral should they remain on a typical residential demand profile. The values of the price bands were:

- High price: 67.20 pence/kWh;
- Mid-price: 11.76 pence/kWh; and
- Low price: 3.99 pence/kWh.

The middle price point was used as a baseline tariff and the high and low price points were used to generate trial events of two distinct types, adapted to specific use cases:

- Constraint Management (CM): These events aimed to measure the potential for dToU demand response to relieve constraints on the distribution network; and
- Supply Following (SF): These events probed the response of households to simple high or low price signals of varying duration. The objective of these events was to quantify the potential of dToU demand response to aid in energy balancing.

Consumers were incentivised to change their electricity consumption in reaction to changes in the electricity tariff. Over the trial year, 95% of households saved money relative to what they would have spent had they been on the standard flat tariff of the non-ToU group.
A household engagement ranking metric was developed to allow the stratification of results by responsiveness to the different price bands. 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, and each dot represents a single household. We expected a negative kW response on the chart (i.e. consumers turning-down or choosing not to use appliances) to the high price signal, no changes to the default price, and a positive kW response (i.e. consumers re-scheduling laundry cycles and energy usage) to the low price. The results show a large variance across the group, but the key outcome is that the high price response available from residential households is 56W of load reduction available during winter (or 0.056kW as shown in Figure 1 above), which drops to 34W (or 0.034kW) during summer.

In addition to the HH data analysis, survey data was collected from the majority of these households and 37 semi-structured in-depth interviews were carried out to gain insight into the experiences of residential customers participating on a dToU and to further understand observed patterns in demand response. The LCL appliance ownership and usage survey, part of the broader household survey, represents one of the most comprehensive surveys in Great Britain of appliance ownership ever conducted. There was both a very positive customer reaction and strong acceptance of the dToU tariff. One of the most impressive findings from the survey was the very high rate of endorsement (91% of those interviewed) and, moreover, agreement that dToU “should be the standard tariff for everyone” (81%). Also 79% reported that Economy Alert was not experienced as complex in the course of living day-to-day with the tariff. Furthermore, trial participants valued the educational role of the dToU, especially for young household members.

A key outcome from the LCL project has been to quantify the potential expected response from domestic customers to time varying pricing. However, the project has also contributed to understanding that the dToU structure is multi-purpose, allowing multiple parties in the energy chain, including suppliers, to call off independent events. This will also be critical to establish a viable business case for Time-of-Use tariffs, once smart meters are rolled out, across the full energy chain.

LCL has contributed significantly to forming a robust deployment strategy for how DNOs can utilise DSR services in order to defer capital expenditure or to manage network constraints during construction and maintenance outages. Based on I&C customers contracted for both turn down and generation DSR services, this approach has been validated through real-world experience within the LCL project. The project developed and executed contracts over three winter and three summer seasons and at peak had over 18MW under contract across 37 customer sites and provided over 300MWh of support to the London Power Networks (LPN) network. The project outputs include consideration of:

- Compliance with the philosophy of the current network security standards (ER P2/6 and ETR130);
- The DSR capabilities available from the I&C customer market; and
- Considerations of the marginal increase in likelihood of interruptions from relying on non-asset based solutions outside the DNO’s immediate control.
This project also demonstrated that the deployment of DSR has the potential to deliver financial benefits to both customers and DNOS and to provide network planning and control engineers with a new option to manage network constraints.

A new set of reliability factors that can be used to assess the contribution of DSR to security of supply has been derived based on real performance data. Utilising the DSR event data from the LCL trials, this project presents a methodology for assessing the contribution of DSR to security of supply. These reliability factors, or “F-factors”, are presented in Table 1 and have been derived using a similar approach to the Energy Network Association’s technical report ETR130. These factors represent the ratio of the capability of DSR to the rated capacity of DSR and will provide DNOS an understanding of the amount of “over-procurement” likely to be required to ensure the necessary response will be delivered.

Table 1 Reliability factors or “F-factors” for I&C DSR types

<table>
<thead>
<tr>
<th>DSR Type</th>
<th>Number of DSR facilities</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Diesel</td>
<td>70%</td>
</tr>
<tr>
<td>CHP</td>
<td>69%</td>
</tr>
<tr>
<td>Demand Reduction</td>
<td>54%</td>
</tr>
</tbody>
</table>

The project has also looked at how the uncoordinated use of large scale DSR by multiple parties may form new synergies but has also tested the potential for conflicts. The overwhelming finding is that, should DSR become widely used by multiple actors, coordination at the procurement stage will provide a significant benefit without large capital investment in shared service platforms (e.g. for coordinated dispatch).

The experience and findings from LCL have allowed UK Power Networks to adopt DSR as a business as usual activity. This has culminated in savings within the 2015 RIIO-ED1 business plan submission of £12m across the LPN licence and a total of £43m across all three of UK Power Networks’ licensees during the period.

LCL has considered the rapid growth in DG and the expectation is that this will continue. The project has also measured how the diversity of DG has changed. In recent years, there has been a steep increase in the number and capacity of DG connected to distribution networks in Great Britain, including in the LPN licence area. As shown in Figure 2, the capacity now installed in LPN is around 1,250 MW, with a large proportion being diesel and Combined Heat and Power (CHP) plants. This represents slightly more than one fifth of the maximum demand. A combination of factors, including targets for 25% of energy in London to come from decentralised sources by 2025, means further growth in DG is expected.
The project looked in detail at how DNOs may consider the use of active and passive management of DG in the climate of significantly increased volumes making application for connection at both LV and HV network levels. Through significant levels of monitoring of DG plant connected to the network, LCL has contributed a significantly better understanding of the generation profiles in urban networks and their operating annual cycles. As discovered through the trials, having enhanced visibility could, potentially provide support to the network, and having control of the generation sites could potentially increase the security of supply.

**Electrification of Heat and Transport**

With the anticipated growth and proliferation of EVs and HPs, previous assessments carried out by the DNO community and academics in Great Britain have identified the likelihood of the additional load from EV charging and HP operation requiring capital investment in the network. These studies modelled reasonable representations of the networks in Great Britain and used estimated profiles of both HPs and EVs in their base assumptions. LCL, on the other hand, has taken empirical data, derived by monitoring a substantial number of residential and commercial vehicles and HPs as part of the projects trials and modelled the impact on actual networks in London. The EV data collected in the LCL trial covered three broad areas: (i) metered EV charging data for 72 residential and 54 commercial charging points; (ii) data on charging events collected at 491 public charging points; and (iii) vehicle logger data capturing driving and charging behaviour for 30 EVs. Key information recorded included active power for charging, timing and duration of charging events and the energy required by EVs during charge events. The project has been able to:
• Replace the representative networks and estimated load profiles used in previous work with real measured network and load profiles representing actual customer usage patterns. See Figure 3 for details of the diversified residential EV user profile;

• Examine the impact of these new loads on power quality and provide evidence to support the previous anecdotal conclusions; and

• Derive new EV profiles, such as the ones presented in Figure 3, and diversity figures, as illustrated in Figure 4, which had not been available until now.

The LCL project provides guidance on the impact of EV and HP loads on a distribution network and provides recommendations as to how to incorporate these into the forecasting, connections, planning and demand monitoring processes.

**Figure 3: Average residential charging profiles per EV for different days of the week**

![Average residential charging profiles per EV for different days of the week](image)

**Figure 4: Diversity factor for different subsample sizes of residential EVs**

![Diversity factor for different subsample sizes of residential EVs](image)
The electrification of road transport has become a prominent element of the decarbonisation policy in the energy sector, accompanied by a high share of low-carbon electricity supplied by renewable generation and technologies such as nuclear and Carbon Capture and Storage. An electrified transport sector would be characterised by significant flexibility. This means that vehicle charging time could be varied and creates opportunities for utilising efficient charging strategies to optimise electricity generation and enhance the usage of network capacity. Unlike conventional vehicles, EVs offer their users the convenience of charging at home without the physical presence of the driver, although this comes at the cost of lower driving range and longer charging times.

**Network Planning and Operation**

LCL set out to understand how smart meters may be used to plan and manage distribution networks as well as to demonstrate how they may facilitate the implementation of Time-of-Use tariffs. The smart meter installations, numbering over 5,500, were recruited from a balanced demographic sample of EDF Energy customers, ensuring a true representation of the LPN area and allowing further extrapolation or representation for other network areas. The demographic sampling utilised the commercially available CACI Acorn categorisation and was later represented by a more macro grouping. Figure 5 describes the smart meter trial recruitment including the dToU subset described earlier.

*Figure 5: Recruitment of Smart Meters and dToU trialists within the LPN area*

Through extensive analysis of the results, LCL has provided insights into the different consumption patterns and the level of demand diversification across seasons, during on-peak and off-peak hours, and between weekends and weekdays. Based on the actual energy consumption measurements and the extensive survey conducted, the LCL project has enabled pioneering analysis to correlate consumption patterns with household’s income levels and occupancy class.
In Table 2 below, we present the maximum diversified peak demand per household across three different LCL Acorn income classes and three different occupancy levels. This demonstrates significant variability of diversified peak demands (from 0.54 kW to 1.78 kW) associated with different demographics. This analysis highlights the benefit of knowing an area’s demographic and consumers’ behaviour, alongside the likelihood of take-up of new loads such as EVs, HPs and solar PV.

**Table 2: Diversified peak for different LCL Acorn classifications (rows) and occupancy of premises (columns)**

<table>
<thead>
<tr>
<th></th>
<th>1 person</th>
<th>2 person</th>
<th>3+ person</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Adversity</strong></td>
<td>0.54 kW</td>
<td>0.89 kW</td>
<td>1.12 kW</td>
</tr>
<tr>
<td><strong>Comfortable</strong></td>
<td>0.64 kW</td>
<td>0.98 kW</td>
<td>1.34 kW</td>
</tr>
<tr>
<td><strong>Affluent</strong></td>
<td>0.79 kW</td>
<td>1.16 kW</td>
<td>1.78 kW</td>
</tr>
</tbody>
</table>

In addition to the smart meter trials, LCL has studied and reports on the effect which energy efficiency may have on the network in the future. As part of their business plan submissions and capital investment plans, DNOs made a firm assumption on domestic energy efficiency and load reduction in the same way that they historically have had to make a firm bet on economic growth and consequent load growth. These assumptions, in some cases, can make a substantial difference to the agreed capital investment plan. The findings from LCL show significant potential for Great Britain, based on three case studies: reference, which considers only currently implemented policies; future energy efficiency policies, and implementing the best technology available; and is illustrated below in Figure 6 for both 2020 and 2030 scenarios.

**Figure 6: Domestic lighting and appliance energy efficiency impacts on peak demand**
In addition to the work on smart metering and energy efficiency, LCL established three areas in London, named the Engineering Instrumentation Zones (EIZs) illustrated in Figure 7. In the EIZs LPN 11kV feeders (three in total), were instrumented in order to understand active and reactive power flow per feeder. This also enabled a new application of state estimation to be tested and verified.

**Figure 7: Engineering Instrumentation Zones (EIZs) of the Low Carbon London trial**

Furthermore, the project installed monitoring to all outgoing ways of the associated substations and voltage monitoring devices at the end points of the LV circuits emanating from these distribution substations. This allowed for unprecedented insight into the nature of diversity and the balance of load on the system as well as voltage profiles along the final LV feeders.

The voltage level on selected areas of the London LV network was analysed and shown to generally be compliant with statutory voltage limits. 78% of the phases measured at the end of feeders had no readings at all outside of statutory limits and only 0.35% of all the phases measured showed more than 1% of readings outside of statutory limits using 10 minute resolution data. All voltage compliance issues are being investigated.

In general, voltage on the LPN network is towards the higher end of the allowable limits. This means there is less headroom (margin compared to the upper limit) than legroom (margin compared to the lower limit) suggesting that the LPN network is more sensitive to an increase in embedded generation than increased demand from other technologies such as EVs and HPs. However, the lower voltage limit is currently responsible for more voltage excursions.

A state estimation algorithm was also tested, in order to estimate load flows and voltages. Results on simple radial feeders demonstrated that measurements of power flow even into neighbouring substations at which no monitoring was present and no analogues available were accurate to within +/-20% on 90% of occasions. This could be of assistance to control engineers in understanding what load they might be about to pick up when sectionalising the network following a fault, and deciding on how to sectionalise the network. Additional monitoring may be required at teed-off circuits, which tend to increase uncertainty in the results.
Future Distribution System Operator

In future DNOs are likely to play a far more active role in managing load and generation on the network than is currently the case today, and the LCL project has demonstrated new organisational relationships within the current industry structure. Specifically, LCL has demonstrated commercial relationships with four energy aggregators and bilateral arrangements with 37 demand response sites; control room integration with two demand response sites; system integration with a Charging Network Operator (CNO) in order to call off demand response from electric vehicle charge posts; and a shared or multi-purpose Time-of-Use tariff with one of the major energy suppliers (EDF Energy).

The project has also clearly demonstrated areas in which closer inter-working will be required in future, either within the same or any modified industry structure. Over the next decade, DNOs will be procuring DSR as a new entrant alongside the largest single procurer today, the Great Britain System Operator (GBSO), National Grid. By the mid-2020s, modelling carried out within LCL suggests that energy suppliers will be an equally significant player as the GBSO is today, as they seek to balance a much larger proportion of renewable generation within the generation fleet.

Finally, the project has demonstrated that under all future uptake scenarios, there is potential for DNOs and smart grids to contribute a 5g/kWh reduction in Great Britain’s carbon intensity, if the appropriate business cases can be made to support the roll-out of controlled EV charging, Time-of-Use tariffs and controllable electric heating in the home.

The project also explores approaches that are alternate to the current planning practices. These topics are explored in detail and include:

- Option Value of DSR and Min/Max regret investment;
- New approaches for considering reliability of DSR;
- Implementation aspects of relying on commercial arrangements, such as controlling pay-back or the resumption of energy use after DSR events, and methods of measuring baselines amongst industrial and commercial customers whose energy usage varies considerably from one to another; and
- Virtual power plants.

SDRC to Report Mapping

Low Carbon London, in common with other Low Carbon Network Fund Second Tier projects, had a number of Successful Delivery Criteria (SDRC) which it needed to meet. Included as an appendix to this summary report is a SDRC to report mapping that has been included to aid the reader in their navigation around the comprehensive suite of documents published by the LCL project.
We’ve now tested organisational relationships that will provide the baseline for the future – we want to see industry, policymakers and local communities working together to make smart grids a reality.
In 2009, Ofgem introduced the Low Carbon Networks (LCN) Fund to encourage DNOs to try out and explore new technologies, operating and commercial arrangements, and find the best value for money for network users while helping to tackle climate change.

The LCN Fund has the purpose of enabling DNOs to understand how they can best invest and what are the best commercial arrangements and operating strategies to provide security of supply at value for money as Great Britain (GB) moves to a low carbon economy.

A key feature of the LCN Fund is the requirement that learning gained from projects can be disseminated, in order that customers gain significant return on their funding through the roll-out of successful trials and the subsequent network savings and/or carbon benefits.

The fund consists of £500m, of which £320m was destined to an annual competition for the allocation of funds to cover ‘flagship’ projects, known as Second Tier projects. In 2010, when the first competition took place, UK Power Networks, in collaboration with eleven partners, submitted a project proposal that would address all main concerns with the low carbon impact on the electricity networks, and covered many of the ‘smart grid’ technologies.

As described in Figure 8 the low carbon transition will not only impact electricity generation, by setting high renewable energy targets, but will change the way consumers use electricity both by increasing the use of electric vehicles and heat, as well as having more visibility through the smart meter roll out. This will all have a direct impact in communities and work places and presents challenges and opportunities for improved network use and operation. The Low Carbon London project outlined these challenges, and proposed solutions, and designed a set of trials that would address most of the obstacles and uncertainties around the low carbon transition. The London network proved to be the perfect test bed for addressing most dense network challenges and having access to different customers for the proposed trials. In December 2010, London Power Networks was awarded funding for this £28.3m project.

In parallel, Northern Power Grid presented the proposal for a project that would tackle some of these low carbon challenges with different alternatives. The project Low Carbon Network Revolution was awarded funding to work with different partners on designing and implementing complimentary trials which in conjunction with the LCL findings have informed the industry on the impact of the low carbon future. This project included different demand side response solutions, including a static time of use tariff and specific trials on smart appliances.
A Low Carbon UK

**UK Low Carbon Transition Plan / UK Renewable Energy Strategy / Low Carbon Industrial Strategy / Low Carbon Transport: A Greener Future**

**Reduction of the UK’s CO₂ emissions** - 34% reduction of CO₂ emissions by 2020 & greenhouse gas emissions by at least 80% by 2050, both set against a 1990 baseline - UK Climate Change Act 2008

**Security of the UK’s energy supply** - reduce net UK gas demand by 29% in 2020, increase of low carbon generation, investment in new nuclear power stations and Carbon Capture & Storage (CCS) (Funding up to four ‘commercial scale’ demonstrations)

**Strong UK Low Carbon economy** - UK to be world centre of the green economy - the global market for low carbon goods and services could grow to over £4.3 trillion by 2015

**Affordability** - transition to a Low Carbon UK must be affordable

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**40% of UK’s electricity from low carbon sources by 2020**

**30% of UK’s electricity from renewables by 2020**

**Challenges**
- Demand response to provide backup for intermittent renewable
- Demand response to provide balancing services
- Flexible demand to provide reserve and frequency regulation services

**Solutions**
- Demand to follow generation - Demand Side Management, storage, Demand Response, Distributed Generation, Tariffs etc.

**Opportunities**
- DSM used to reduce the need for network reinforcement
- Learning opportunities

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**Localised increase levels of distributed generation (including micro-generation)**
- FIT (≤ 5MW low carbon electricity generators)
- Renewables Obligation Certificates (ROCS)

**Challenges**
- Reverse power flows, increase fault-levels, voltage constraints, instability (e.g. angular stability and low frequency)

**Solutions**
- Active network management to facilitate connection of DG
- Fault current limiters
- GenAVC
- Dispatch / curtailment

**Opportunities**
- DG to support localised demand and hence reduce the need for network reinforcement
- Learning opportunities

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**Electrification of Heat & Transport**
- 14% CO₂ reduction from transport by 2020
- Test bed UK (£400 million on infrastructure deployment, EV incentives (Plug-In Car Grant) and EV technology development)
- Plugged in places (funding for EV re-charging infrastructure)

**Challenges**
- High demands & new network peaks, network thermal constraints

**Solutions**
- Smart EV Charging
- Smart Heat Storage / control, Tariffs

**Opportunities**
- Smart control to reduce the need for network reinforcement
- Learning opportunities

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**The Low Carbon London Project**

**LPN - Existing network challenges**
- Summer peak demand
- High load densities in the central area
- Very high levels of utilisation
- Sustained high levels of load growth
- High fault levels
- Very high levels of quality of supply must be maintained
- Very high costs of reinforcement due to severe limitations on availability of service routes and substation sites
- LV interconnected MV network design precludes transfer capacity - main substations becoming heavily loaded
- Aging LV network - LV faults
- Interconnected LV network
- Limited of non-existent LV network monitoring
- Lack of visibility of latent generation

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**Figure 8: Challenges, opportunities and solutions of the low carbon electricity sector at 2010**
Roll out of Smart Meters
- Mandated for all residential customers & majority of SMEs by 2020
- Mandated Smart Grids functionalities

Opportunities
- Increase LV network visibility
- Customer demand profile
- Support smart control of EVs and Heat Pumps
- Enable use of ToU tariffs
- Monitoring impact of DG in load and voltage profiles
- Enable Demand Side Management
- Learning opportunities
- Enabling Smart Grids

Challenges
- Customer engagement

Opportunities
- Demand Side Management
- Energy Efficiency for Demand reduction
- Community involvement
- Learning opportunities

Why London?
- **Mayor of London’s CO₂ reduction targets** - London generates around 47.5 million tonnes of CO₂ a year, which the Mayor of London aims to reduce by 60% by 2025 compared to 1990 levels
- **London has the highest CO₂ emissions** per km² in the UK
- **PiP & Mayor’s Transport Strategy** - 2,500 Charging Points by 2013 & 25,000 by 2015; 100,000 electric vehicles by 2015; London Congestion charge exemption for EVs
- **Mayor’s Renewable Targets** - 25% of electricity and heat to be supplied from local generation by 2025, 68MW of photovoltaic, 6MW of micro-wind electricity generation, 168MW of heat demand to be supplied by ground or air sourced heat pumps
- **GLA Energy Efficiency** and Community engagement programmes (improving EE in 14,000 existing residential homes across 10 London boroughs)
- **LDA’s Green Enterprise District** - New low carbon developments and redevelopments in the Lower Lea Valley and Thames Gateway
- **Combined impact** of electric vehicles, heat pumps, and decentralised/micro-generation on an already **highly utilised network**

Transforming Workplaces & jobs
- 13% CO₂ reduction from workplaces by 2020
- 500,000 additional UK jobs in the renewable energy industry by 2020

Transforming homes and communities
- 29% CO₂ reduction from homes by 2020
- Zero carbon homes from 2016
- Tackling fuel poverty (Warm Front & Energy Efficiency)
- Cert & CESP

The Low Carbon London Project

DNOs to cost effectively manage the above challenges using smart grid solutions where appropriate, in order to **enable the UK Low Carbon Transition Plan**
As the Low Carbon London Project was set up, 2011 was focused on signing the contracts with the partners, designing the trials and building the infrastructure required to implement them. By the beginning of 2012, the trials were set up so that we could recruit customers. Specifically, we worked with EDF Energy to engage over 5,000 domestic customers in the smart meter trials, of which over 1,100 were involved in the dynamic Time-of-Use trial. Likewise, the industrial and commercial DSR and the Distribution Generation monitoring trials were designed and ready to be recruited. LCL has successfully monitored electric vehicles, public charge posts and domestic heat pumps that were all recruited in collaboration with several partners throughout 2012 and 2013. By Q2 of 2012, the Operational Data Store (ODS) was implemented as a repository for all of the experimental data and the Learning Laboratory in Imperial College London was set up. 2013 was the year where all the trials and data collection took place, and 2014 was when both ICL and UK Power Networks analysed the data culminating in this suite of reports summarising the learnings.

There are eleven partners that have collaborated throughout the LCL Project:

- CGI (formerly Logica);
- EDF Energy;
- EnerNOC;
- Flexitricity;
- Imperial College;
- Institute for Sustainability;
- Mayor of London / Greater London Authority;
- National Grid;
- Siemens;
- Smarter Grids Solutions; and
- Transport for London.

To address all the case studies presented in the LCL Project proposal, and addressing the challenges described above, the LCL results have been categorised into three themes:

A. Distributed Generation and Demand Side Response

This group of reports present all the findings from both, the residential and industrial and commercial demand side response trails, as well as the findings and analysis of having more distributed generation connected to the network. Specifically:

- A1 Residential Demand Side Response for outage management and as an alternative to network reinforcement – presents the impact on the distribution network of a wider scale roll out of a dynamic Time-of-Use tariff;
- A2 Residential consumer attitudes to time varying pricing – outlines the results from the quantitative and qualitative assessment from the survey and interviews of customers on the dToU trial;
- A3 Residential consumer responsiveness to time varying pricing – explicitly describes the quantitative results in terms of load reduction and load shifting;
- A4 Industrial and Commercial Demand Side Response for outage management and as an alternative to network reinforcement – presents the results from the I&C DSR trials and outlines the key considerations for DNO implementation of DSR and P2/6 planning assessments;
- A5 Conflicts and synergies of Demand Side Response – analyses the impact of multiple parties contracting DSR and potentially accessing the same resource;
- A6 Network impacts of supply-following Demand Side Response report – focuses on the impact of low carbon led generation and the DSR market as DNOs will experience it in the years ahead;
- A7 Distributed Generation and Demand Side Response services for smart Distribution Networks – presents the quantitative analysis of the I&C DSR trials and introduces alternative baselining techniques;
- A8 Distributed Generation addressing security of supply and network reinforcement requirements – looks at the impact of having more DG connected to the distribution network and the potential improvement on security of supply;
- A9 Facilitating Distributed Generation connections – determines how smart technologies such as Active Network Management can facilitate more capacity on the urban network for generation, and
- A10 Smart appliances for residential demand response – outlines potential response from smart appliances.
B. Electrification of Heat and Transport

As described before, 72 domestic EVs and 54 commercial EVs were monitored, and the data was complemented by 1,408 public EV charge posts; also, 21 heat pumps were closely monitored to present key findings. All the findings related to electric vehicles and heat pumps from these trial results were thoroughly analysed and the key findings are presented in this group of reports. Specifically:

- B1 Impact and opportunities for wide-scale Electric Vehicle deployment – focuses on presenting the results from the EV monitoring trials and the analysis on diversity and profiles for the observed loads;
- B2 Impact of Electric Vehicles and Heat Pump loads on network demand profiles – considers and models the expected impact of EVs and HPs at a wider scale based on the trial findings;
- B3 Impact of Low Voltage – connected low carbon technologies on Power Quality – covers the detail of the power quality of LCTs and the impact on the LV network;
- B4 Impact of Low Voltage – connected low carbon technologies on network utilisation – analyses the direct impact of high EV and HP uptake on the network at scale; and
- B5 Opportunities for smart optimisation of new heat and transport loads – outlines the potential smart solutions such as Time-of-Use tariffs and ANM to address the impact of EVs and HPs on the network.

C. Network Planning and Operation

This group of reports cover the analysis from the smart meter trials, focused on understanding the use of smart meter data, as well as the impact of energy efficiency measures on customer’s electricity consumption. Based on optimal use of enabled monitoring, the reports also cover the state estimation concept. Specifically:

- C1 Use of smart meter information for network planning and operation - presents the analysis of domestic customer’s profiles as well as the voltage assessment from the engineering instrumentation zones;
- C2 Impact of energy efficient appliances on network utilisation – outlines the potential for reduction on energy use by efficient appliances;
- C3 Network impacts of energy efficiency at scale – models the impacts and benefits of appliance efficiency on the distribution network;
- C4 Network state estimation and optimal sensor placement – describes a new approach to calculate the status of the networks without having full visibility of the network using a state estimation technique, and
- C5 Accessibility and validity of smart meter data – assesses the validity of the smart meter data gathered throughout the trials.

D. Future Distribution System Operator

Finally, as all the trials have concluded, the LCL Project has integrated six final reports that will address the future implications of the Distribution Network Operators and their transition to the future Distribution System Operators. In summary:

- D1 Development of new network design and operation practices – outlines the key changes and considerations required for implementing the LCL findings into planning and network operation processes;
- D2 DNO Tools and Systems Learning – describes the Information Systems and Operational telecom systems required for the integration of smart meters and smart grid solutions;
- D3 Design and real-time control of smart distribution networks – Considers the potential new planning approaches including Option Value of DSR and Min/Max regret investment;
- D4 Resilience performance of smart distribution networks – develops the assessment of reliability for DSR and introduces an alternative approach to network reliability consideration;
- D5 Novel commercial arrangements for smart distribution networks – defines some of the key considerations for the electricity industry on how dynamic networks will require more commercial flexibility; and
- D6 Carbon impact of smart distribution networks – quantifies the carbon impact of deploying a full smart network and presents the impact of LCLs trials.

The following sections of this report describe the key findings from all the reports referenced above and has been structured by the same themes. Please note that throughout the LCL reports, all prices are in 2012/13 terms unless otherwise stated and NPV values consider the full life of the assets, commonly 45 years.
Timeline

- Learning Dissemination
- LCNF Bid Process
- LCNF Approved
- I&C DSR Trials
- SM Deployment
- Trial Design and Deployment
- Recruitment for SM & ToU Trials

Timeline:
- 2010
- 2011
- 2012
2013  2014  2015

GB’s First dToU Trial

EV & HP Trials

Inform RIIO-ED1

Project Reports

All Project Trials Active

SM & ToU Trials
**Project Highlights**

**Demand Side Response – generation**
New commercial contracts developed by the trials, which pay large customers to reduce their electricity consumption on demand or generate electricity locally, will save UK Power Networks’ customers £43m by 2023.

**Instrumenting a Smart Grid**
The project installed monitoring equipment in three unique areas of London to enable visibility of the network, from grid supply points to the last point on the Low Voltage (LV) networks. This provided significant new data on voltage levels which is fundamental to understand a future with many low carbon technologies connected to the network and helped us understand approaches to monitor the network efficiently, by determining what the best place is to locate monitoring using techniques such as state estimation.

**Dynamic Time-of-Use tariff**
We have proved “wind-twinning” tariffs can shift residential demand. Customers can be incentivised by Time-of-Use tariffs to ‘do their washing on windy days’, using more electricity when wind power is plentiful. During high price periods participants reduced their average peak demand by up to 8%. This demonstrated their potential to take part in domestic demand response initiatives.

**Demand Side Response – demand**
Thirty seven participants, including hotels, shops and visitors attractions took part in the demonstrations.

**Distributed Generation**
Industry standards must be revised to accommodate new evidence and account for new types of generation connecting to the network. DNOs must engage with connected customers, as well as new developers, to benefit from the potential DG contribution to enhance network performance.

**Project Highlights**

19  |  Introduction
Tangible transformer headroom is required to account for cold conditions when load diversity amongst heat pumps is reduced (due to reduced efficiency); even at lower levels of 5% uptake at domestic level.

We collected data from one of the largest EV trials in Britain, concluding that mass charging of electric vehicles will have a substantial impact on electricity networks at 0.3kW per household, but the trials showed this will be more manageable than feared.

A survey of appliances in 2,830 homes across London collected the most accurate data on electricity consumption since the 1980s. Based on the analysis of this data we estimate there could be a 10TWh saving in electricity consumption by 2020 by switching to more efficient appliances.

We installed 5,500 meters with EDF Energy and secured concurrent data from a further 10,000 British Gas smart meter customers. Together we believe they are the largest smart meter trial data set in Britain. Going forward, smart meters will not only enable dynamic tariffs, but they will also give us insight to better understand consumption, network conditions such as voltage, and the uptake of low carbon technologies.

We found stark differences in winter electricity consumption between different income groups and occupancy in the homes. High income households offer the greatest potential for reductions in electricity consumption, but more importantly, houses with more than three people living in them have a higher potential for energy efficiency.

Active Network Management systems were tested which have potential to increase by a third the amount of locally-produced electricity being connected to the London network.

Active Network Management 

Electrification of transport 

Smart meters 

Network planning 

ANM/network operation 

Energy efficiency
Report User Guide

Demand Side Response and Distributed Generation
A1. Residential Demand Side Response for outage management and as an alternative to network reinforcement
A2. Residential consumer attitudes to time varying pricing
A3. Residential consumer responsiveness to time varying pricing
A4. Industrial and Commercial Demand Side Response for outage management and as an alternative to network reinforcement
A5. Conflicts and synergies of Demand Side Response
A6. Network impacts of supply-following Demand Side Response report
A7. Distributed Generation and Demand Side Response services for smart Distribution Networks
A8. Distributed Generation addressing security of supply and network reinforcement requirements
A9. Facilitating Distributed Generation connections
A10. Smart appliances for residential demand response

Electrification of Heat and Transport
B1. Impact and opportunities for wide-scale Electric Vehicle deployment
B2. Impact of Electric Vehicles and Heat Pump loads on network demand profiles
B3. Impact of Low Voltage – connected low carbon technologies on Power Quality
B4. Impact of Low Voltage – connected low carbon technologies on network utilisation
B5. Opportunities for smart optimisation of new heat and transport loads
Network Planning and Operation

C1 Use of smart meter information for network planning and operation
C2 Impact of energy efficient appliances on network utilisation
C3 Network impacts of energy efficiency at scale
C4 Network state estimation and optimal sensor placement
C5 Accessibility and validity of smart meter data

Future Distribution System Operator

D1 Development of new network design and operation practices
D2 DNO Tools and Systems Learning
D3 Design and Real-time control of smart distribution networks
D4 Resilience performance of smart distribution networks
D5 Novel commercial arrangements for smart distribution networks
D6 Carbon impact of smart distribution networks
Demand Side Response and Distributed Generation

The project investigated two categories of Demand Side Response (DSR): residential DSR, based on dynamic tariffs, and Industrial and Commercial (I&C) DSR based on agreed contracts with large customers.

From a residential perspective, the trials implemented the first dynamic Time-of-Use tariff in GB. This created the opportunity to design and demonstrate a tariff which still reduced bills, but could serve multiple purposes: it could help reduce peaks on the network, increase demand on windy days, or reduce demand on days when little wind power is available. As a result, during high-price periods participants reduced their average peak demand by 8%, demonstrating their potential to take part in the DSR initiatives as well as the ability to match customer’s electricity consumption with the availability of wind power.

For the I&C DSR trials we had agreements with 37 different customer sites to support the network by either turning down their electricity demand or running their on-site generator. A total of 185 DSR events were called, and the vast majority of sites provided a response. Between a third and half of the sites reduced demand either ahead of or on time and held it below the agreed figure until the required time or even longer. Based on LCL results, UK Power Networks has committed to implement I&C DSR to save £43m of investment in real assets, that we would otherwise have had to make between now and 2023.

Finally, in recent years, there has been a steep increase in the number and capacity of Distributed Generation (DG) connected to distribution networks. In London, a total of 1,250MW is installed, with a large proportion being diesel and Combined Heat and Power (CHP) plants. By integrating monitoring data from 15 sites, covering both CHP and Photovoltaic (PV) generators, with other generation data from the industry, LCL has derived behaviour profiles for these technologies. As further growth in DG is expected, distribution companies have the challenge of accommodating additional capacity. However DG can provide valuable support to local supplies if we can be certain of its performance. Having greater visibility of when plants are operating or down for maintenance, as well as using Active Network Management to recognise the current configuration of the network could allow additional generators to connect.
A1 Residential Demand Side Response for outage management and as an alternative to network reinforcement

A2 Residential consumer attitudes to time varying pricing

A3 Residential consumer responsiveness to time varying pricing

A4 Industrial and Commercial Demand Response for outage management and as an alternative to network reinforcement

A5 Conflicts and synergies of Demand Side Response

A6 Network impacts of supply-following Demand Response

A7 Distributed Generation and Demand Side Response services for smart Distribution Networks

A8 Distributed Generation addressing security of supply and network reinforcement requirements

A9 Facilitating Distributed Generation connections

A10 Smart appliances for residential demand response

Demand Side Response and Distributed Generation | 24
2.1 Residential demand side response

2.1.1 Baseline demand
Demand side response (DSR) is defined as the change in demand induced by a price event, which requires a comparison of the observed demand with a hypothetical baseline demand for if the event had not occurred. A linear regression model was created to compute a per-household baseline demand based on that household’s relation to the non ToU group, modulated by additional temporal factors (hour of day, day of week). By coupling the baseline to the behaviour of the non ToU group, it correctly accounts for non-standard days (e.g. bank holidays) and special events.

2.1.2 Consumer engagement
Consumers were incentivised to change their electricity consumption in reaction to changes in the electricity tariff, which was designed to be cost-neutral for households with average consumption levels. Therefore a reduction in the annual bill on the dToU tariff compared to the flat rate tariff is a first indicator of consumers engaging with the trial. Over the trial year, 95% of households saved money relative to what they would have spent had they been on the standard flat tariff of the non ToU group.

Although the observed decrease in annual bills is a good indicator of overall engagement, this does not necessarily extend to individual households. For example, consumers that are often away during the evening are likely to have missed the CM-type evening peak trials, resulting in lower average bills. To classify the engagement of individual households with the trials a measure of responsiveness to dToU signals was developed. It 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 9: Household engagement rank against measured DSR, by price band

Figure 9 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, and 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, it was found that 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 report A3 [9], results are often reported for the most engaged 25%, 50% and 75% of households in addition to the whole trial group (100%). This will allow other researchers and readers to make their own assessment of future potential by considering variables such as tomorrow’s consumers being increasingly energy-aware and performing better than today’s consumers, moving the median response.

2.1.3 Reduction of peak demand levels

The CM events were consistently able to reduce peak demand levels.

Figure 10 shows a CM event designed to achieve weekday evening peak reduction over two consecutive days. The background colour indicates the active price band and the dark line shows the observed demand levels. The inferred changes in demand compared to the baseline are drawn in orange (increase) and blue (decrease). The lighter curve shows the same results restricted to the 25% of best responding households.
Figure 10: A CM event showing evening peak reduction over three consecutive weekdays. The lighter shaded Increase, Reduction and Actual indicate the response from the most engaged 25% of households (Source: LCL Report A3).

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 11: Mean change in demand over the high price period of the CM events (listed by event label). Bars, from lighter to darker shading, represent the average for subgroups of the most engaged 25%, 50%, 75% and 100% of responders (Source: LCL Report A3).
Figure 11 depicts the observed changes in consumption during high price periods, for each of the CM-type events in the trial. The event label ‘$P_x xD x$’ includes the number of consecutive days (‘$xD$’) on which peaks were targeted. The results demonstrate a robust reduction in average load of approximately 0.05 kW/household, which more than doubled to a range of 0.08-0.22 kWh/household for the subpopulation of the 25% most responsive households. Such demand reductions may be considered material for future network planning.

2.1.3.1 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 12 breaks down the average change in demand by half-hourly settlement block, for both high (orange) 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.

The demand reduction potential (in orange) 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 0.12 kWh/household during these periods, compared to 0.05 kW/household for the average household. The strong 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.

Figure 12: Full year mean DSR by 30-minute settlement block 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 (Source: LCL Report A3).

The ability to increase demand levels was fairly constant during the waking hours of the day, at a level of 0.05 kW/household across all households and exceeding 0.15 kW/household for the most responsive households. During the night-time even the best responders do not achieve an increase of 0.05 kW/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.
2.1.3.2 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 13: 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 (Source: LCL Report A3).

That such a situation is not hypothetical is borne out by the low price event shown in Figure 13, 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 compared 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.

2.1.3.3 Socio-economic factors hardly affect response magnitude

The responses of the targeted SF trials were analysed against two principal parameters that are known to be strong indicators of energy consumption: household occupancy (1, 2, 3+) and a socio-economic classifier based on the Acorn system. The three socio-economic groups – Affluent, Comfortable and Adversity – can be interpreted as a rough indicator of wealth.
Figure 14 shows the average demand response for these classes. Perhaps surprisingly, the socio-economic class had no significant effect 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 target peak hours. 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.

2.1.4 Attitudes to time-varying prices

As part of Low Carbon London a residential dynamic Time-of-Use (dToU) tariff was trialled [9] with the aim of measuring consumer’s willingness to engage with dynamic electricity pricing. This is the first trial of a dynamic Time-of-Use electricity tariff with UK households. It was conducted by a partnership of industry stakeholders organisations and academia. The London distribution network operator (DNO) and project coordinator was UK Power Networks. Key partners in the design and implementation of this trial included:

- Imperial College, London (ICL): report author and project academic partner;
- EDF Energy: retail energy supplier;
- Siemens: Information and Communication Technology (ICT) framework; and
- CGI: smart meter head end set-up and management.

Report A2 [1] described learning from the trial and is in many ways a complement to its companion report, A3, Residential consumer responsiveness to time-varying pricing [9]. The latter report addresses questions of responsiveness to the price signals by analysis of consumption data from smart meter data. Report A2 [1] addresses the experiences and attitudes of households on the residential dToU trial. In some ways the separation of consumption practices/behaviour and attitudes is an artificial one, ‘engagement’ spans behaviour, attitudes and understandings. Report A2 aims to add some understanding to what goes on inside the ‘black box’ of the home by looking at how responsiveness is achieved and how households experience this novel tariff. In doing so it relies heavily on trialists’ self-reports from interviews and surveys.
The scheduled rollout of smart meters to all UK households by the end of 2020 opens the door to smart tariffs and dynamic electricity pricing. Domestic consumers are generally positive about smart meters [3] and previous trials of dynamic and Time-of-Use (ToU) tariffs have found public acceptance and responsiveness [4]. Most Time-of-Use pricing trials have, however, investigated static ToU to reduce fixed peaks in demand; the lack of predictable patterns in the price signals for wind-following is a potentially important difference for consumers. Such dynamic ToU tariffs have yet to be offered or trialled in the UK and debate and controversy over consumers’ appetite for the perceived complexities, risks and fairness remain. The GB context for electricity demand and dynamic pricing also differs to that of less temperate North America where most dynamic pricing trials have been conducted. How would GB households respond to price signals to follow wind energy? What are the challenges for such tariffs and how can engagement be maximised? Report A2 [1] begins to answer these questions.

Analyses show a large majority of households on the trial modified their consumption behaviour in response to the dynamic pricing signals and also made financial savings over the 12-month trial period. The interview and survey data on household engagement found that while the unpredictability of the price events was commented on by trialists, dToU was not reportedly experienced day-to-day as complex. Findings shed light on the potential of dynamic pricing for wind-following and how such tariffs might be delivered and supported with appropriate technology to maximise take-up, engagement, and consumer benefit, and so can help to inform future trials and energy policy.

Further details about the measured responsiveness to the dToU tariff is covered in LCL Report A3, Residential consumer responsiveness to time-varying pricing [9]. Report A2 [1] summarised the aspects of engagement concerned with the attitudes and experiences of the households on the trial, these are summarised below, followed by specific recommendations for future trials.

2.1.4 Main findings on consumer attitudes to dToU

- **Very positive trialist reaction to dToU**: Perhaps the stand-out finding is the degree of positive reaction to dToU from trialists who were, it is worth emphasising, quite heavily incentivised to sign-up to Economy Alert (as the LCL dToU tariff was known) and therefore not necessarily pre-disposed in favour of dToU at the outset. The list below shows the range of these positive endorsements of the dToU tariff by trialists. It will be interesting to see, in the future, if these figures are affected by alternative price points and rate schedules but there is no reason to believe that these aspects of the Economy Alert tariff design were especially attractive. Indeed, certain changes to the tariff design used in the LCL dToU trial could result in even greater levels of satisfaction (e.g. lower High-rate, fewer evening peak-time High-rate events, and better on-going feedback about savings). Findings include original insights into some non-financial and more psychological benefits to consumers. Four points worth emphasising from the table below are,

- **Strong acceptance and support of dToU**: One of the most impressive findings from the survey was the very high rate of endorsement of this item (91%) and, moreover, agreement that dToU “should be the standard tariff for everyone” (81%). This indicates strong potential support for cost-reflective pricing which is viewed as fairer and/or promoting efficiency. Awareness and debates about cost-reflective pricing have some way to go but this is an extremely encouraging starting point;

- **dToU was not experienced as complex**: Despite the admission that calculating costs and comparing with other tariffs is far from simple, 79% reported that Economy Alert was not experienced as complex in the course of living day-to-day with the tariff. In the current UK context of efforts to make energy tariffs simpler and more transparent (under Ofgem’s Retail Market Review), findings suggest that greater consumer engagement supports greater acceptance of, or even an appetite for, some types of complexity and the two need to be seen in tandem. The importance of communicating to trialists the reasons underlying rate changes in the schedule (see below) further underscores that in some cases transparency is more important than simplicity;

- **dToU helps households in planning and organizing (77%) and motivating them (80%) to get chores done.** This was one of the most striking survey results. In contrast to fixed ToU price signal occurring at the same time every day, it is possible that some of the motivating aspect of dToU is linked to the unpredictability and complexity of the schedule. Many trialists spontaneously reported experiencing an element of fun, challenge or game-like aspects to fitting behaviour around the dynamic high and low rates suggesting that dToU has greater potential than fixed ToU for subtle gamification;

- **Trialists valued the educational role of dToU, especially for young household members.** 77% of survey respondents who had young household members to whom this could apply (n=85) agreed or strongly agreed that, “Being on Economy Alert was a valuable experience for the teenagers/young adults in our household to learn about the costs of energy before they leave home and pay bills themselves”.

- **Very positive trialist reaction to dToU**: Perhaps the stand-out finding is the degree of positive reaction to dToU from trialists who were, it is worth emphasising, quite heavily incentivised to sign-up to Economy Alert (as the LCL dToU tariff was known) and therefore not necessarily pre-disposed in favour of dToU at the outset. The list below shows the range of these positive endorsements of the dToU tariff by trialists. It will be interesting to see, in the future, if these figures are affected by alternative price points and rate schedules but there is no reason to believe that these aspects of the Economy Alert tariff design were especially attractive. Indeed, certain changes to the tariff design used in the LCL dToU trial could result in even greater levels of satisfaction (e.g. lower High-rate, fewer evening peak-time High-rate events, and better on-going feedback about savings). Findings include original insights into some non-financial and more psychological benefits to consumers. Four points worth emphasising from the table below are,

- **Strong acceptance and support of dToU**: One of the most impressive findings from the survey was the very high rate of endorsement of this item (91%) and, moreover, agreement that dToU “should be the standard tariff for everyone” (81%). This indicates strong potential support for cost-reflective pricing which is viewed as fairer and/or promoting efficiency. Awareness and debates about cost-reflective pricing have some way to go but this is an extremely encouraging starting point;

- **dToU was not experienced as complex**: Despite the admission that calculating costs and comparing with other tariffs is far from simple, 79% reported that Economy Alert was not experienced as complex in the course of living day-to-day with the tariff. In the current UK context of efforts to make energy tariffs simpler and more transparent (under Ofgem’s Retail Market Review), findings suggest that greater consumer engagement supports greater acceptance of, or even an appetite for, some types of complexity and the two need to be seen in tandem. The importance of communicating to trialists the reasons underlying rate changes in the schedule (see below) further underscores that in some cases transparency is more important than simplicity;

- **dToU helps households in planning and organizing (77%) and motivating them (80%) to get chores done.** This was one of the most striking survey results. In contrast to fixed ToU price signal occurring at the same time every day, it is possible that some of the motivating aspect of dToU is linked to the unpredictability and complexity of the schedule. Many trialists spontaneously reported experiencing an element of fun, challenge or game-like aspects to fitting behaviour around the dynamic high and low rates suggesting that dToU has greater potential than fixed ToU for subtle gamification;

- **Trialists valued the educational role of dToU, especially for young household members.** 77% of survey respondents who had young household members to whom this could apply (n=85) agreed or strongly agreed that, “Being on Economy Alert was a valuable experience for the teenagers/young adults in our household to learn about the costs of energy before they leave home and pay bills themselves”.

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Table 3: Summary of trialists’ pro-dToU attitudes and perceived benefits (n=708) (* ‘No Replies’ and ‘Neither agree nor disagree’ not shown)

<table>
<thead>
<tr>
<th>Survey statements about dynamic-ToU tariff</th>
<th>% Agree or Strongly Agree</th>
<th>% Disagree or Strongly Disagree</th>
</tr>
</thead>
<tbody>
<tr>
<td>Greater sense of control</td>
<td>71</td>
<td>24</td>
</tr>
<tr>
<td>Worth the hassle</td>
<td>67</td>
<td>28</td>
</tr>
<tr>
<td>Enjoyed some aspects</td>
<td>55</td>
<td>39</td>
</tr>
<tr>
<td>No reduction in quality of life</td>
<td>75</td>
<td>19</td>
</tr>
<tr>
<td>Do not find tariff complex</td>
<td>79</td>
<td>16</td>
</tr>
<tr>
<td>Effort sustainable long-term</td>
<td>79</td>
<td>15</td>
</tr>
<tr>
<td>Good for motivating us to get chores/activities done</td>
<td>80</td>
<td>7</td>
</tr>
<tr>
<td>Helped planning/organizing/rememebing activities/chores</td>
<td>77</td>
<td>10</td>
</tr>
<tr>
<td>Taught young about the cost of energy</td>
<td>71</td>
<td>14</td>
</tr>
<tr>
<td>We miss some things about being on dToU</td>
<td>53</td>
<td>13</td>
</tr>
<tr>
<td>Some new practices persisting beyond end of trial</td>
<td>70</td>
<td>30</td>
</tr>
<tr>
<td>Reduced overall electricity consumption</td>
<td>63</td>
<td>30</td>
</tr>
<tr>
<td>Renewables link would make me more likely to sign up</td>
<td>59</td>
<td>32</td>
</tr>
<tr>
<td>Renewables link would make me more likely to adapt behaviour</td>
<td>60</td>
<td>31</td>
</tr>
<tr>
<td>Would want to stay on dToU</td>
<td>77</td>
<td>18</td>
</tr>
<tr>
<td>dToU should be offered to everyone</td>
<td>91</td>
<td>5</td>
</tr>
<tr>
<td>dToU should be the standard tariff for everyone</td>
<td>81</td>
<td>14</td>
</tr>
</tbody>
</table>

- **Explanation of the reasons behind dynamic ToU is required:**
  
  - **Ambivalence about unpredictability:** The characteristic of dToU for supply following that distinguishes it from fixed ToU is that the times of rate changes are unpredictable. It appears a potentially serious issue that having more predictable timing of rate changes was the most commonly endorsed suggestion (from a list of seven) of things that might help their household respond better in the future. 68% reported that they would be more likely to sign-up to dToU if the rate changes were more predictable. But this must be seen alongside other survey responses – both the predominant wish to remain on dToU and also more positive interpretations of superficially negative aspects of dToU such as unpredictability and complexity.

  - **Communicating the reasons behind the rate changes will increase engagement:** The schedule of rate changes on the dToU trial was unpredictable and no clear explanation was provided to trialists for why the rate was higher at some times than at others. In interviews and surveys some trialists reported irritation with the schedule and its lack of transparency and the suspicion that the rate changes were scheduled to benefit the supplier. This is unsurprising in a context of consumer mistrust of suppliers [5] and scepticism that the benefits of the smart grid will be shared with consumers [6], but the unpredictability of dynamic ToU schedules brings these issues of trust to the fore. A strong piece of learning from the
LCL dToU trial is that consumers are likely to engage more with dToU if the reasons and rationale for the tariff design, rate change events etc. are explained clearly. The absence of any reasons or rationale for rate changes in the LCL dToU trial was reportedly felt by many trialists and there was a tendency for mistrust and cynicism about profit motives, and frustration to be expressed in the absence of explanations. If the rate changes are seen as happening at certain times for a good reason (“I just need to know that it’s been done for an efficient reason”), then tolerance of the unpredictability, complexity, limited notice period, etc. appears to follow.

- **Efficiency, citizenship and support for renewables all have significant potential to engage consumers in dToU**, as evidenced by the survey findings in this trial: 60% of survey respondents said they would be more likely to sign-up to dToU and more motivated to be flexible if there was a link with renewables; almost 70% would be motivated by “helping society use energy more efficiently”. Earlier work on UK households’ attitudes towards energy system change also points to the importance of initiatives being seen as consistent with consumers’ values [7]. Survey responses also indicated that stimulating debate about fairness and efficient usage of resources would be a valuable step towards public acceptance and support for dToU. This potential for engaging with households on the basis of their “civic relationship with the grid” [7], rather than purely narrow financial interests also has support from qualitative work for the another LCNF project, the Customer-Led Network Revolution.

**Insights into what helped and limited households respond to rate-changes:**

- **Feedback was well-received but improvements possible:** the in-home-display (IHD) was found to be clear and useful for acting on rate-changes but suggestions for improvements were also common. Similarly, the monthly feedback letter was generally well-received but highlights even more the variation in preferences between different households. On-going feedback about financial savings made benchmarked against a flat-rate tariff was not given to trialists and this is considered essential for future trials (as it would undoubtedly be for a real-world commercial dToU tariff). The most prominent suggestion for improvements to the IHD for dToU were for it to have a traffic light display for present tariff rate as well as, or instead of, for present load.

- **The use of timers for shifting was limited.** Timer functions/devices were reportedly used by only a small minority of households, even in households who owned appliances with timers, approximately 40% never used that function. Reasons for limited use of timers included their perceived complexity of use and the noise from wet appliances during the night. This suggests more user-friendly design, and improvements in acoustic insulation of appliances and or buildings could support greater use of night-time surplus electricity.

- **Flexibility in who uses appliances is limited:** Although 21% of responding households on the trial reported making changes to who uses appliances in order to better respond to dToU, approximately 20% of households agreed that having fixed roles for who uses appliances were a limiting factor and the fact that they were not able or willing to adapt these roles is potentially very interesting, both sociologically and from the point of view of increasing Demand Response (DR) in the future.

- **The reported most/least flexible practices were as expected:**
  - **Most flexible:** Wet appliances were reported to be the easiest to shift. Lighting, cooking and showering were reported as the hardest to shift, however some shifting of even these was reported.
  - **Least flexible:** Interestingly, the supposedly hard-to-shift cooking practices are reported to be flexible (more than ‘occasionally’) onto Low-rate for 35–40% of trialists who owned electric oven or hob. However, further analysis will aim to check if these self-reports corresponds to actual shifting/consumption behaviour.

- **Reduction in overall consumption commonly reported but not yet assessed:** Further work is needed to corroborate this with actual consumption data but it is interesting in broadening-out the impact of dToU beyond load-shifting practices and into a wider interest in greater efficiency, reduction/curtailment. Indeed, it is interesting that using less lighting came out as the most commonly-reported action to take advantage of rate-changes. This is a curtailment/reduction behaviour, not a shifting behaviour, which suggests potential links between dToU and future take-up of low-energy (LED) lighting and other energy-efficient products and appliances.

- **The self-reported data seems to be in agreement with the measured DR,** e.g., about which days/times were preferred for alerts but more cross-comparison of measured DR with survey responses will be carried out.
• **DR on future trials should be greater.** For a number of reasons to do with trial design and the context DR should be greater in the future. These reasons include: the sample excluded some potentially price-sensitive types of households; recruitment was heavily incentivised so likely included households not disposed to dToU (early adopters of dToU would be more engaged and responsive). self-reports suggest that the guarantee of reimbursement if worse off may have reduced responsiveness in some households; better engagement and responsiveness are possible with better feedback and advice; the time-limited nature of the trial is likely to have reduced some forms of investment in the trial compared to an open-ended or longer-term commitment to dToU; assessing the reduction in overall consumption was not possible and this is likely to have reduced the measured DR for high-rate periods; the future context for dToU is likely to see increases in the value of DR and the technology and norms supporting dToU engagement.

2.1.4.2 Recommendations for future dToU trials and areas for further development

The following recommendations are made for future trials of dToU tariffs. Some of the following points are discussed above.

• **Provide a clear rationale and reasons for rate changes.** Clearly explaining the link between the rate changes on supply-following tariffs and renewable energy generation should increase engagement for the majority of trialists. This should also reduce frustration with unpredictability, complexity and the limited notification period. This will require a general increase in consumers’ understanding and awareness of the energy system and market and the importance of resource management. Consumers should also feel (justifiably) confident about the fairness of both more cost-reflective pricing and also how the benefits from DR are being shared among stakeholders (consumers, supplier, DNO etc.), as suggested by the respondents and interviewees of this study and previous research [6],[7].

• **Promote awareness and debate about the energy system.** Given very low levels of consumer awareness about almost all aspect of the energy system and the challenges it faces, promoting education and debate about these challenges, the need for change and more active consumers is highly recommended.

• **Link supply-following tariff to real-world conditions of renewable generation (or a sample of past renewable generation data) so that the price signals are based on actual variability in renewables and demand.** It would also be valuable in terms of trialling the back-office systems necessary to support this. It would be a challenge to add this layer is necessary to take learning towards a real-world, commercially feasible stage of development.

• **Consider carefully the effect of price points on savings and feedback.** One of the clearest caveats concerns the limits to what should be inferred from the actual financial saving made by households on dToU. This was largely a function of the competing aims of investigating responsiveness to dToU and attitudes to it and the needs of recruitment. More detailed analyses of trial data are on-going and should produce some more definite insights but future trials should carefully consider the impact of tariff design and delivery on both the study of responsiveness and studying attitudes to dToU tariffs. Better savings should lead to more positive, more motivating feedback to consumers.

**Participant Recruitment**

• **Minimize exclusion criteria:** including some of households excluded from the LCL dToU trial (pre-payment customers, dual fuel and some type of vulnerable customers etc.) is recommended to allow better assessment of the range of distributional impacts especially for price-responsive or early-adopting households.

• **Minimise effect of incentives on sample and behaviour.** In the LCL dToU trial participants effectively self-selected to be in the dToU group and also (by declining) to be in the non-ToU group. The preferred approach to recruitment depends upon the research questions and aims of the trial: if the trial wishes to see the distributive effects for a broad range of different types of households then recruiting a broad sample may be the main challenge and incentives justifiable. Ideally, random allocation of participants to control and ToU groups would be used but as this is often unfeasible, large incentives can also mitigate self-selection. If, however, the main interest lies in the behaviour of early adopters in a context as near to real-world as possible, then incentives should be avoided in so much as they could influence recruitment, behaviour and drop-out rates. There would be some merit in studying early adopters given that dToU will be opt-in for the foreseeable future. LCL used substantial incentives for recruitment to dToU. While this helped recruit participants and also made a broader sample possible, minimizing incentives would be preferable due to the buffering effect of incentive payments on price signals and therefore behaviour. Recruitment in future trials should consider the possibility of dispensing with, or at least minimizing, incentives and guarantees. Dropping out of the trial would need to be possible, and uninfluenced by payments, in order to study churn rates, which was not possible on the LCL trial. As dToU becomes less of a novelty, the need for incentives and guarantees should diminish.
• **Recruit directly onto dToU trial.** In the LCL trial households were first recruited for smart meter installation and then dToU trialists were recruited from this pool of households. As the smart meter rollout progresses it will be unnecessary to recruit in two phases and this will be more cost-effective, reduce self-selection issues (at least for the control group).

• **Obtain baseline consumption data to assess overall reduction.** The period for obtaining baseline data for households was severely reduced in the LCL dToU trial; ensuring a substantial period for baseline data is available should become much easier as the number of smart meters installed grows. Recruitment could be targeted at households for which 12 months of smart meter data is already available.

• **Make the trial open-ended.** While this may be difficult in practice, a trial which does not have a predetermined end-date would be preferable as some participants indicated that they may have made some investments of effort or money to better respond to rate changes if the trial had not been a temporary situation. For example, investment in the up-front cost for LED lighting, or when replacing an appliance purchasing a more expensive model with a timer function; in non-financial terms, trialist may confront household members who are not cooperating with the rate changes.

• **Improve feedback.** Throughout the trial period participants should receive monthly feedback on their savings benchmarked against both previous consumption (to reflect savings from reduction) and relative to a standard flat-rate. As this was lacking in the LCL dToU trial it would be interesting to assess the impact this feedback has on motivation and engagement. Improvements to the IHD would also be ideal such as a traffic light indication of current tariff rate. If possible, disaggregated feedback on relative consumption of appliances would be ideal but as this is challenging, written advice on the relative costs of running different appliances would be worthwhile alternative. Further improvement to feedback for dToU mentioned by trialists would be to have feedback available online and via smart phones. Comparative feedback—where households can see how their efforts compare to similar households in their area—would be another valuable form of feedback for dToU. Studying preferences for different forms of feedback would be a worthwhile avenue for future research.

• **Include advice on load-shifting and reduction.** Given dToU trialists written advice suggesting ways of achieving DR would also enhance the trial. Information on the relative consumption of appliances would also be of interest and value to many consumers.

Household dynamics: Future work could also aim to explore whether dToU might play a role in the possible loosening of fixed roles within the household governing who uses appliances and the potential to increase responsiveness accordingly.

### 2.1.5 Reliability of residential demand side response

Report D4[12] discusses the effects of dynamic Time-of-Use tariffs on network constraint management. A statistical analysis of the Low Carbon London trial data was performed in order to quantify opportunities and risks from a reliability perspective.

First, the performance of the dToU trial group on the LCL constraint management trials was analysed with the aim to identify a model for the tariff-induced load reduction. The observed demand response was consistent with a 7.8% reduction in demand during the peak period (95% confidence range: 7.1%-8.4%). A predictive model was constructed, suggesting that future constraint management events would result in a demand reduction between 4.6% and 11.0% demand reduction (95% confidence).
The next step in the analysis was the extrapolation beyond the LCL trial setup, considering an arbitrary number of households of unknown composition. This reflects the situation where the DNO arranges for high-price signals to be broadcast to a set of households in order to alleviate network constraints. To quantify the extent to which demand response can alleviate network constraints, the capacity contribution of demand response was defined as the change in required network capacity that results from the use of the dToU signal. Here the required capacity is defined in probabilistic terms as the capacity that is needed in order to satisfy the expected maximum demand plus a safety margin to cover random load fluctuations to within a stated level of confidence (i.e. after-diversity maximum demand).

It was shown that the capacity contribution of demand response can be decomposed into two components: mean response and variance response. The variance response results from changes in the variance of consumption levels between households. In the case of the LCL constraint management trials the high-price signal was always found to reduce the variance of household consumption levels, even more than suggested by the mean load reduction. This is consistent with trial participants opting to switch off or postpone the use of discretionary large loads, thus reducing the propensity of large load peaks. The variance response thus has the effect of boosting the capacity contribution of demand response, as a lower capacity margin is required to anticipate peak load fluctuations.
To get an impression of the impact that the variance reduction effect has on the capacity contribution, its value was computed across a range of aggregation levels. Furthermore, the consumption distribution of the dToU trial group for each of the events was used as a set of hypothetical collective responses from which the households were sampled, effectively providing a sensitivity regarding response variability. In all cases the variance contribution boosted the capacity contribution, but by an amount that decreases with the aggregation level. A maximum boost of 25% compared to the mean response was observed at a mean demand response capacity of 50 kW, decreasing to 10% at 1 MW and 5% at 10 MW. These are significant figures, but they are outweighed by the observed variability in the mean response itself, with fluctuations of 40% or more around the expected value. Therefore, in most cases the additional contribution of variance response may be ignored without material consequence.

Finally, the focus shifted to potential conflicts between the DNO’s local network management aims and the suppliers’ incentive to respond to wholesale electricity markets. At times of abundant wind power availability, the suppliers may broadcast low prices to consumers in order to incentivise demand shifting. However, the resulting additional demand may boost local demand far above previously anticipated levels and thus interfere with network operations.

The extent to which demand may be boosted by low prices was analysed using data from the LCL Supply Following dToU trials. It was confirmed that there is a considerable risk of increasing the load on distribution networks, with 22 out of 48 low price events achieving load levels that are consistent with daily peak load or higher levels, and 10 of those showing load levels that are significantly higher than the baseline. The observed enhanced load peaks all occurred on weekday evenings and weekend afternoons, but their occurrence does not appear to depend on the magnitude of the expected peak demand of the day. We note that these findings must be taken in the context of the trial: changes to the price signals may increase or reduce motivation to respond, while increased penetration of home automation may make it easier for consumer to respond in the hitherto inconvenient times (e.g. sleeping or working hours).

2.2 Impact of smart appliances

The main objective of report C2 [10] was to quantify the potential impact on peak demand in a typical section of a distribution network once domestic appliances are substituted with more energy-efficient alternatives. In order to develop planning assumptions, Distribution Network Operators (DNOs) need to forecast the effects of energy efficiency measures as part of long-term demand forecasts, particularly the effects of replacement of appliances with more energy-efficient appliances. Most importantly, energy efficiency assumptions should be translated into impacts on peak demands, which represent the key input parameter for distribution network planning. Furthermore, impact on network losses should be considered given that the largest proportion of network losses is in Low Voltage (LV) networks.

Improving energy efficiency has been prominent on the energy policy agenda in the recent decades, because of its potential to reduce the investment in energy infrastructure while also reducing energy cost to consumers. In general, in order to establish a cost-benefit case, savings from implementing energy efficiency measures should be compared with the cost associated with achieving these measures. In the context household appliances, there is a broad agreement that energy efficient lighting and wet and cold appliances are likely to be economically efficient and deliver overall net benefits. This has driven the thinking behind obligatory labelling on new appliances for sale showing their energy efficiency, and obligations placed on energy suppliers to support domestic energy efficiency. While the potential for energy savings from energy efficient appliances is relatively well understood, the impact of a widespread uptake of highly efficient appliances on the peak demand in distribution networks has not been previously quantified with sufficient detail, and this comprises the key contribution of this report.

Energy efficiency has become an integral part of appliance manufacturing culture. The initial success of the labelling scheme through the 1990s was founded upon the elimination of the worst performing appliances and modest changes in appliance design, largely centred on changes to project cycle and temperature set paints. Some contemporary appliances, however, appear to have undergone what approaches a bottom up re-design, and this represents a second generation in the development of energy efficiency. Given that the usage patterns of different appliances vary throughout the seasons and days of the week, predicting the effects of energy efficiency upon network utilisation is not a straightforward task.

The LCL trials relating to smart appliance use are described in section [25]. The modelling approach adopted in report C2 [10] uses detailed survey data from the household survey carried out alongside the Low Carbon London Smart Meter trial, to build accurate distributions of the number of appliances of each type in each household. This is combined with Office of National Statistics (ONS) data on daily household activities on one hand, and independently developed physical models of appliances on the other, in
order to produce diurnal appliance load profiles. This can be thought of as bottom-up modelling, which simulates the activity of individual appliances in individual households and then aggregates and studies their effect on the distribution substation. The effects of appliance technology substitution are evaluated against a baseline case that has been calibrated against the national household appliance survey.

The conclusions from the study of a LV network beneath an 11 kV/415 V distribution transformer show that the practical effects of energy efficiency have a varying impact on the residential load profile. A set of demand profiles is provided which represents possible changes to demand under different appliance and lighting technology adoption scenarios. What emerges from the analysis is that there is significant latent potential for load reduction if efficient appliances are adopted, and that each category of appliance has a specific effect on load profiles.

Lighting technology, despite previous replacement campaigns by the electricity retailers in the UK, still has considerable potential for energy reduction, in particular through the introduction of Light Emitting Diode (LED) and Compact Fluorescent Lamp (CFL) lighting, which present significantly lower consumption than conventional light bulbs. Even more importantly, because of a high coincidence factor of lighting loads (i.e. a high likelihood of lighting devices being switched on during network peak demand), lighting is responsible for a considerable proportion of residential peak demand. The analysis presented in the report estimates the peak demand reduction potential from efficient lighting in a residential area may reach up to 15%.

Although the substitution of cold (e.g. fridges) and wet (e.g. washing machine) appliance technologies both provide peak demand reductions, 3% and 2% respectively, they are considerably lower than those identified from lighting technology replacement.

The critical insight provided by the appliance survey also suggests that this level of impact on peak demand will not be uniform across the entire London population, as the effect in those areas characterised by higher income population and higher occupancy is likely to be more prominent due to higher appliance ownership rates.

This analysis further demonstrates that the combined reduction in demand could lead to reduction in LV distribution network losses in domestic areas of more than 30% during winter. From the customers’ perspective, for each 100 units of energy they save through energy efficiency measures, they would see the effect of roughly 101 units on their energy bill, since the cost of buying energy to cover the losses has also reduced.

From the DNO perspective, lighting technology substitution is the most likely to affect peak demand going forward. Nevertheless, the timeline in which this substitution may progress is uncertain as it is difficult to forecast the rate of replacement, which will be driven by a number of economic and policy factors. DNOs will need to continue to monitor the timing and uptake of both energy efficient appliances and new loads such as heat pumps and electric vehicles as they form their load forecasts.

### 2.2.1 Demand diversity of households

The LCL report “Quantifying demand diversity of households” [11] focussed on performing a demand diversification analysis on Low Carbon London (LCL) demand data collected via smart meters across 3437 households over the calendar year of 2013. The original dataset is segregated in a number of subsets to enable detailed analysis of demand diversification patterns across different seasons, days (weekdays and weekends) and hours (on-peak and off-peak).

We first present and analyse the different electricity consumption profiles focusing on the extraction of diversified peak household demand metrics. Subsequently, we present and apply three methods for the calculation of diversified demand and coincidence factor profiles, examining how they vary as a function of households. The three methods applied are:

1. Conventional statistical analysis based solely on smart-metering measurements;
2. Computations based on fitting of parametric gamma-distribution curves to capture infer-variability of peak demand across different combinations of consumers, and
3. The use of a truncated copula C-Vine approach, enabling sampling of new demand patterns at arbitrarily high densities via a parameterized statistical model trained on smart-metering measurements.

The aim of applying the above methods is to present different approaches to quantifying system demand diversity and assess the robustness of the estimates. Most notably, the truncated C-Vine method constitutes a novel statistical approach that enables the exploration of a large number of potential demand scenarios, enabling us to resolve the potential bias of an analysis relying on limited datasets. We demonstrate that the observed and recorded smart-metering dataset is consistent with highly expanded set of possible electricity consumption scenarios, generated via the high sampling density enabled by the truncated C-Vine method. This shows that the LCL smart-metering trial gathered a sufficiently large dataset across sufficiently-

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varying conditions, i.e. a whole calendar year across a sufficiently large number of households of different occupancy levels and wealth status, resulting in high confidence regarding the statistical significance of the analysis presented in the report.

Through extensive discussion of the results, insights towards the different consumption patterns and the level of demand diversification across seasons, on-peak and off-peak hours, weekends and weekdays are provided. Based on the actual energy consumption measurements and the survey conducted, Low Carbon London project enabled pioneering analysis to be undertaken to correlate consumption patterns with household’s income levels and occupancy class.

In the Table below we present the maximum diversified peak demand per household across three different LCL Acorn income classes and three different occupancy levels. This demonstrates significant variability of diversified peak demands (from 0.54 kW to 1.78 kW for customer numbers greater than 200) associated with different demographics. This highlights the benefit of knowing an area’s demographic and consumers’ behaviour and the increasing importance of having smart-metering data to enable informed planning decision.

**Table 4. Diversified peak for different LCL Acorn and occupancy classes based on the C-Vine technique**

<table>
<thead>
<tr>
<th></th>
<th>1 person</th>
<th>2 person</th>
<th>3+ person</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Adversity</strong></td>
<td>0.54 kW</td>
<td>0.89 kW</td>
<td>1.12 kW</td>
</tr>
<tr>
<td><strong>Comfortable</strong></td>
<td>0.64 kW</td>
<td>0.98 kW</td>
<td>1.34 kW</td>
</tr>
<tr>
<td><strong>Affluent</strong></td>
<td>0.79 kW</td>
<td>1.16 kW</td>
<td>1.78 kW</td>
</tr>
</tbody>
</table>

Furthermore, with the aid of diversified peak demand results we demonstrate that rule-of-thumb approaches that have been traditionally used in the past for planning purposes may no longer be relevant and should be updated according to actual emerging data and measurements.

The presented results can serve as a useful starting point for informing the accurate characterisation of demand diversity, enabling planning engineers to tailor distribution networks’ designs according to its demonstrated needs. It is envisaged that with the advent of the smart-grid paradigm and increasing rollout of smart meters and other related Information and Communication Technology (ICT) infrastructure, the reliance on actual measurements and application of the discussed metrics and analysis methodologies will increasingly become an integral part of the distribution planning process. We demonstrate that the diversified household peak for large number of consumers during winter conditions is found to be 1kW as opposed to 1.5 kW to 2 kW frequently used in the UK. Furthermore, this finding provides important benchmark for network planning and the analysis of the domestic demand response presented in report A3 [9]. However, diversified peak demand for small number of consumers was found to vary significantly.

### 2.3 Industrial and Commercial Demand Side Response

In report A7 [13] Low Carbon London has pioneered the development of formal contractual arrangements for the provision of generation-led and demand-led Demand Side Response (DSR) services to DNO. In this context, the key objective of report A7 [13] was to understand and characterise the performance of DSR services within the distribution network, in order to inform future smart distribution network operation and planning. It begins with an analysis of baselining methods for DSR and is followed by an analysis of data gathered from the Low Carbon London trials to assess the performance of the participants. Use of a bottom-up physical model to demonstrate the assessment of the potential demand-led DSR capacity of a building is then described. DSR currently provides more than 500MW of capacity for Short Term Operating Reserve (STOR) in the UK. However, there are still barriers to participation in DSR projects, especially regarding demand-led DSR. The report ends with a qualitative analysis of these barriers.

Recognising that the baselining method is key to measurement of DSR performance and payback (or ‘take-back’), present baselining practice, including both asymmetric and symmetric high five of ten is investigated. It is found that asymmetric High Five of Ten (HFoT) performed less well than symmetric HFoT in the trials, but that the difference was small. In addition a novel method called ‘Similar Profile Five of Ten’ (SPFoT) was developed for Low Carbon London. This is based on selecting
daily profiles of similar shape to build the baseline and is designed specifically for analysing the hotel events in the trials which were observed to have very varying profile shapes. However, across all events it was found that the advantage of SPFoT was marginal. Our analysis of different baselining methods suggests that it might be appropriate to consider alternative methods depending on the shape characteristics of a sites load.

The demand response trials exercised both genuine demand-led and generation-led DSR and were designed to relieve network congestion at peak. By measuring compliance\(^1\) it was found that, for the most part, the resources performed as requested. Generation-led DSR was found to deliver 95% of the requested response for 30% of summer 2013 and winter 2013/14 events, and demand-led DSR was found to deliver 95% of the requested response for 48% of these events. Considering generation-led DSR alone, performance was significantly better in summer than winter with sites delivering 95% of the requested generation in 42% of summer events, but only 18% of winter events. Similar 95% compliance figures for demand-led DSR are 62% for summer and just 8% for winter. The small winter figure may be driven by the lack of chiller load in winter and the predominance of gas in heating of buildings.

Within the Low Carbon London trials, events were triggered in one of two ways: (1) in the first case, events were triggered manually, to simulate a control engineer reacting to existing SCADA alarms and then telephoning the demand-side aggregator or an individual site to trigger an event; (2) dedicated SCADA alarm was generated which was immediately shared with the aggregator or an individual site in order to request a response. The control engineer was notified rather than expected to intervene. This second case was enabled by Active Network Management (ANM)\(^2\) equipment. ANM triggered calls delivered the requested response for 86% of events, phone triggered calls, 93%. The number of events trialled at each site was quite small and no site stood out as having a particularly poor response to calls. For these reasons it is not possible to differentiate between individual sites in terms of response to calls. The majority of events started on time or early, which is re-assuring for the DNO’s considering DSR as a tool for managing network capacity. As expected, the ANM triggered events were somewhat more timely. Compliance for ANM triggered events during winter events was much worse on average than it was during the summer trials.

Trials included 11 hotels and these responded to calls to turn down during summer 2013 and winter 2013/14 in 83% of events - lower than average. Late starting was also a problem with 15% of these events starting late. However, the ability to maintain the required level of turn-down was much better than average, with this achieved in 78% of events.

A novel bottom-up physical model of a building was made for Low Carbon London to assess and analyse the potential DSR capacity of a building. The model is designed for aggregators to understand the potential impact of alternative DSR strategies on the comfort and service levels and quantify the buildings response under different operating regimes and weather conditions. The model would be especially useful in more extreme weather conditions, where historical data may not be available. In addition, by spreading the turn-down around a number of zones, it can be ensured that no single zone becomes uncomfortably hot. This may be a valuable tool for the wider supply chain of demand side aggregators and energy management consultancies as they seek prospect DSR opportunities. This model could also provide information to DSR providers regarding the potential risks to comfort and service levels. Given the data available the model was found to produce robust results, closely replicating the building load for separate events.

Existing practice does not recognise the phenomenon of payback (or ‘take-back’). Payback was, in fact, observed in most demand-led DSR events in the trials, producing sharp peaks that, in the case of the hotel sector, varied between 15% and 270% of the pre-event load. The amount of energy recovered during payback was wide-ranging, but quite small on average, showing that as much as 80% of energy demand was curtailed during events. It was also found that there was a good correlation between the payback peak height and maximum demand-led DSR turn-down for the hotel sector. The level of payback may therefore be predicted, within limits, for a given turn-down.

Finally, a qualitative analysis of barriers to participation in DSR was made. It was found that the most significant barriers related to negative perceptions of potential risks to comfort and service levels, as well as fears around costs, time, equipment and other resources. These negative perceptions were found to outweigh technical and financial barriers to participation.

2.3.1 Reliability of industrial and commercial demand side response

Report D4 [12] analyses the reliability performance of I&C DSR as evidenced in the Low Carbon London trials. Based on the LCL trial data, probabilistic models were constructed and analysed in order to quantify the dependability of I&C DSR for network constraint management.

First, the measured response traces for all sites and each of the trial events were analysed. The variability, magnitude and seasonal dependence of I&C DSR was found to be distinctive for each of the four classes considered: diesel, CHP, HVAC and water pumping stations. Generation-led DSR (diesel and CHP) was found to respond most in line with

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1 Compliance is the percentage of time during a DSR event that a site maintained its turndown or generation above the amount specified by contract.

2 ‘ANM’ is the system installed by project partners SGS to automatically trigger a DSR event when a chosen substation exceeds a load set point.
the contract targets, consistent with their direct control over load levels. 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 response of HVAC and CHP systems differed between summer and winter trials. HVAC 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.

Probabilistic response models were constructed for each DSR type, and separately for the summer and winter trials. The aggregate response of multiple independent units was considered and unit commitment requirements were computed and visualised for a range of target load reductions. It was found that a significant fraction of sites outperformed the contract terms, with HVAC sites during summer having the strongest performance, with reductions up to six times of the contracted amount. The decision whether to take this bonus into account for the construction of probabilistic models has significant implications for aggregate performance metrics.

The numerically computed unit commitment graphs do not provide intuitive insight into the relation between model parameters and aggregate dependability. For this reason, an analytical approximation was developed for the unit requirement curve of independent identical aggregates of DSR sites. A good match with the numerically computed curves suggests that the model may be used as a shortcut to performing full convolutions, especially when absolute accuracy is not required. For example, it may be used to develop an intuitive understanding of the impact of single-unit response parameters on aggregate behaviour, or to embed approximate dependability characteristics in a larger simulation.

Analysis of the response traces also evidenced the occurrence of simultaneous late-start events, involving sites being triggered by single aggregators. This reinforces the need to understand the potentially severe impacts of common mode failures in network management. A basic model for common mode outages was introduced, where sites are distributed over a small number of aggregators. A probability of just 0.5% for the failure of an aggregator to activate its DSR sites has a very large impact on the unit commitment requirements. Depending on the desired confidence level, using a single aggregator may never provide sufficient dependability, whereas good performance is recovered with the use of three independent aggregators.

Finally, 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. 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 is highly variable, but generally characteristic for the site. 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.

2.3.2 Use of demand-led I&C DSR for peak demand management

Turning down thermal load in I&C DSR sites generally results in energy payback. This is an inevitable consequence of the physics of the interaction between heat transfers from the building to the outdoor space and vice versa combined with the objective to follow the target temperature profile. For instance, if the cooling of a building is reduced during e.g. 1-hour period, the indoor temperature will increase and once the reduction period expires the building temperature control will attempt to bring the temperature back to the pre-reduction level as soon as possible. Bringing the temperature down within a short time frame will require more energy than just maintaining the temperature at a constant level, and this will partially offset the energy reduction effected during the 1-hour control interval.

A total of 185 DSR events were called, and the vast majority of sites provided a response. Between a third and half were compliant with every aspect up to 95% - reducing demand either ahead of or on time and holding it below the agreed figure until the required time or even longer.
Figure 16. Example of load recovery with payback for a hotel chiller system (Source: LCL Report A7)

To illustrate this effect further on a realistic example, the chart in Figure 16 is reproduced from [13] and shows the load profile of a hotel participating in a trial during a typical DSR event. At point A the chiller is switched off for just over an hour, switching back on at point B, when the building management system (BMS) starts returning the temperatures to pre-event conditions thus initiating the load recovery process. Since the building has warmed up between A and B, the chiller load rises rapidly to reduce the internal temperature to within the set point. Once this is achieved the load recovers to the baseline at point D. Two characteristic quantities are identified for the load recovery process: the payback peak (C) and the payback energy (area denoted by F).

The trials showed that the energy supplied during the payback phase for thermal loads in hotels and offices was relatively modest in the order of 20% of reduced energy during the event. However, the payback peaks were rather sharp and narrow, varying in height between 15% and 270% of the pre-event load. Aggregation of such high peaks could easily cause local overloading in the distribution network, especially if multiple DSR resources are triggered and released simultaneously.

Payback effect is particularly relevant for the distribution network context. Ignoring payback may result in load reductions during DSR events being accompanied by payback peaks of more than twice the load reduction. Such a phenomenon was visible for nearly all DSR events in the trials involving thermal loads. If these DSR resources are used to manage the peak loading of distribution network, it is obvious that in addition to reducing the network peak during DSR events, they may produce an undesired effect of increased demand during load recovery, potentially creating a new peak that may be above the pre-intervention level. If these resources are to be used for peak demand management efficiently, the payback effect needs to be adequately taken into consideration. This specific feature represents a fundamental difference between demand-led DSR and generation assets, whose operation is typically fully controllable without any payback-like effects.
2.3.3 Key findings

Case studies presented in LCL Report D3 [15] clearly suggest that in order to use demand-led DSR resources with load recovery characteristics for efficient peak reduction, they need to be controlled hours before and after the onset of system peak conditions. Ignoring the energy payback requirements and other DSR limitations may result in suboptimal operating strategies or even increase the peak above the pre-intervention case.

Because I&C DSR resources have specific characteristics such as payback and limited control duration, which make them fundamentally different from controllable generation assets, to achieve a given peak demand reduction the volume of DSR response to be contracted (ignoring any non-responsiveness, compliance and timeliness issues) would generally need to be a multiple of the targeted peak reduction. Contracting with I&C DSR sites therefore needs to acknowledge that their contribution to network management will be a function of:

- DSR penetration;
- Shape of demand profile; and
- Response/payback characteristics: duration of control and payback periods, payback power and energy.

Similar to other flexible demand categories considered in the next section, I&C DSR also require that the network analysis and operation planning are done in a multi-period timeframe, rather than based on snapshots in time, as the studies in this section have clearly presented the importance of temporal links between DSR control decisions in one period and their impact on the resulting demand profile observed several hours later.

All the findings from the trials and the analysis on reliability were used to inform Report A4, Industrial and Commercial Demand Side Response for outage management and as an alternative to network reinforcement. This report outlines a deployment strategy for how DNOs can utilise DSR services in order to defer capital expenditure or to manage network constraints during construction and maintenance outages. This approach has been validated through real-world experience within the LCL project and includes consideration of:

- Compliance with the philosophy of the current network security standards (ER P2/6 and ETR130);
- The DSR capabilities available from the I&C customer market; and
- Considerations of the marginal increase in likelihood of interruptions from relying on non-asset based solutions outside the DNO’s immediate control.

The report also outlines the potential financial benefits to both customers and DNOs and the key considerations to provide network planning and control engineers with a new option to manage network constraints. Specifically, Report A4 describes a methodology for assessing the contribution of DSR to security of supply, resulting in a new set of reliability factors, or ‘F-factors’, presented in Table 5, derived using a similar approach to the Energy Network Association’s technical report ETR130. These factors represent the ratio of the capability of DSR to the rated capacity of DSR and will provide DNOs an understanding of the amount of ‘over-procurement’ likely to be required to ensure the necessary response will be delivered.

Table 5 Reliability factors or “F-factors” for I&C DSR types

<table>
<thead>
<tr>
<th>DSR Type</th>
<th>Number of DSR facilities</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Diesel</td>
<td>70%</td>
</tr>
<tr>
<td>CHP</td>
<td>69%</td>
</tr>
<tr>
<td>Demand Reduction</td>
<td>54%</td>
</tr>
</tbody>
</table>
As described in Report A4, there are three use cases in which a DNO would want to implement DSR:

1. To defer standard planned network reinforcement investment, by reducing net load on a specific part of the network during times of peak load;

2. Supporting planned network outages. While the DNO is carrying out wider network upgrade or reconfiguration works, some network capacity might be unavailable. During these times DSR could again be used to reduce net load, thus reducing the need for more expensive conventional interim solutions (such as an equivalent reinforcement or a leased diesel power generation) or, in the worst case, avoiding the need for a P2/6 derogation; and

3. Managing demand in the interim, when actual load is significantly greater than forecasted load and no reinforcement has been planned. In this case scheduled reinforcement will not be ready prior to the load at a substation exceeding its firm capacity.

A detailed Cost Benefit Analysis (CBA) is also presented in Report A4 for each type of DSR use case scenario, showing that DSR has the potential to deliver financial benefits to both the DNO and customers. Savings are presented both in headline terms over the next regulatory price control period, and also viewed on a strict Net Present Value (NPV) basis for current and future customers over the entire life of the network equipment. In one of the specific case studies, savings of £12m in the ED1 period could be achieved when implementing DSR to defer a planned reinforcement scheme. The potential benefits vary depending upon the existing substation load capacity/load profile and the forecast demand growth. Extrapolative analysis has shown that the net benefits from applying DSR to defer reinforcement are generally higher for substations with a low load factor, specifically substations with less frequent and shorter peaks.

During the LCL trials UK Power Networks contracted DSR services from several customers. Some provided DSR through generation facilities (such as CHP sites with sufficient technical and commercial flexibility, or backup diesel generators) while other customers provided the service through a ‘turn-down’ arrangement where they reduced their electricity demand on request. Although the trials were focused on understanding the reliability of DSR provided by each of these customers, there were examples in which real network constraints were managed with DSR.

To maximise the potential DSR response, DNOs should seek to contract DSR services from as many sources as possible. For example, both demand and generation-led sources of DSR should be considered. Early customer engagement is required for DNOs to make DSR deployment decisions. These decisions will be based on the level and type of response that could potentially be contracted at each substation. This is especially important because DSR providers must be connected to the substation in question in order to provide capacity services.

DSR service contracts should be available for single and multiple scheme DSR providers and made either directly (DNO to provider) or via aggregators. LCL experience in managing such contracts has led to the detailed recommendations for DSR commercial structures and clauses that are presented Report A4. Procuring such DSR services takes a significant amount of resources and time and must ensure that the technical requirements and compliance of the portfolio are met at an efficient cost. This should be considered as part of setting the market engagement strategy and resources should be allocated accordingly.

There are two fundamental stages to implementing DSR. The first is to identify a suitable site and the second is the process of procuring and establishing the contractual agreements required. In UK Power Networks, these stages are currently conducted by the Planning and Network Operation departments respectively. For this stage, data is required to identify locations in which DSR will be most useful and how much capacity will be required to achieve the adequate deferral or to be able to manage the network appropriately maintaining statutory limits. Specifically, the data required includes substation load data, Planning Load Estimates (PLE) load forecast data, required additional DSR in MW, potential DSR sites, and understanding the available DSR resources connected to the site to be managed.

Additionally, as described in LCL Report A4, the project has provided guidelines on what the contracts should consider and what terms and conditions customers and DNOs should commit to. These include defining:

- The length of time that the DSR service can be called for;
- DSR availability fee;
- DSR utilisation fee;
- Duration of the contract; and
- Time to respond.
Specifically, UK Power Networks has developed four DSR contract templates for rolling out this service. There are two types of contracts, either a one-off service which specifies a contract that will be used in a specific time, and a standing framework which enables contracts for a longer period of time. These contracts can be agreed either directly with the customer, or with aggregators. In total, there are four templates:

- **One off service window: DNO - DSR Provider.** Most basic form of DSR contract, derived on LCL from STOR service terms and in-line with recommendations programme learning outcomes;

- **One off service window: DNO - Aggregator.** Expanded to include terms related to portfolio management;

- **Standing framework agreement and associated schedules: DNO - DSR Provider.** A no-commitment framework agreement, outlining all of the basic DSR contract terms and additionally including generic schedules for specifying future service agreements, terms under which service agreements are let, and terms for framework duration and renewal; and

- **Standing framework agreement and associated schedules: DNO - Aggregator.** Standing framework and associated schedules. As with previous but additionally including terms related to portfolio management.

Further variations or clauses may be included depending on the DSR response type (generation or demand-led) and the dispatch system used.

Additionally, LCL has created a tool that looks at the impact of these commercial constraints. Essentially, these terms will have a direct impact upon the extent each contract or customer is able to reduce peak load. Also, the actual portfolio of contracts will also impact the response achieved. For example, procuring 10x 1 MW contracts might offer greater flexibility than procuring 1x 10 MW contracts.

This tool allows the DNOs to choose a substation to investigate the opportunities for implementing a DSR scheme. The user adds the relevant parameters of the substation including a forecast of maximum demand and firm capacity before reinforcement and the details of DSR schemes that might be available (i.e. specifying the commercial constraints).

The inputs defined by the user are characterised as follows:

- **DSR unit characteristics:** including DSR type, availability and reliability factor;

- **Commercial constraints:** including the number of hours for which DSR will run when called, maximum number of events by day, week and season, contracting periods such as summer and winter, and

- **Cost parameters:** including availability and utilisation payments for the DSR contract and operating costs.

The results of the tool are presented as a load duration curve indicating periods in which it is used and the impact on load, as well as a cost benefit analysis that quantifies the amount of reinforcement deferral that can be achieved given the substation growth characteristics and the chosen DSR characteristics.

Finally, continuous work with the industry, specifically with the Energy Network Association (ENA) DSR Shared Services Group (SSG) will help define visibility and interaction between the Transmission System Operator (TSO) and DNO and the appropriate arrangements for potentially sharing services.

""" New commercial contracts informed by the trials will enable us to pay industrial or commercial large customers to reduce power consumption when requested, saving UK Power Networks’ customers £43m by 2023. """
Electrification of Heat and Transport

There are very few Electric Vehicles on the road when we started the project and, as such, the DNOs had little experience with their charging patterns and the load that they might represent on the network. But theoretical studies had already shown that if consumers charged often and frequently, even when it was not necessary – and all at the same time, when they returned from the daily commute – then it would generate a significant strain on the distribution network.

The project monitored 1,408 public charging points, 72 domestic and 54 fleet users, and also carried out a questionnaire-based survey with 41 EV users. The project compared the charging behaviour of domestic EV users who were on a Time-of-Use tariff encouraging charging after 9pm and those who were not. The programme also demonstrated an end-to-end integration between charging points out on the street and the DNO’s control and automation systems which monitor load on the network.

As a result, we will be able to predict much more clearly what the effects of the Electric Vehicle uptake will be. We are expecting instances where we have to strengthen the network in the coming years to accommodate extra consumption from EVs, but we will be able to be more targeted as a result of these findings. We now also have a very clear picture of how to help commercial customers looking to upgrade their depots as they convert their fleet to electric, and public transport fleets changing to electric vehicles, some of which will result in requests for a new or increased capacity connection to the network. Our demonstration of turning down public charge posts in agreement with the charge post operator was also successful, demonstrating end-to-end integration of the necessary IT and electrical equipment.

Finally, our heat pump monitoring trials have concluded that there are varying levels of power quality disturbance caused by HPs, but clustering, specifically during extreme cold conditions, could become problematic. Tangible transformer headroom is required to account for cold conditions when load diversity amongst heat pumps is reduced (due to reduced efficiency); even at lower levels of 5% uptake at domestic level.
B1 Impact & opportunities for wide-scale EV deployment

B2 Impact Electric Vehicle and Heat Pump loads on network demand profiles

B3 Impact of low voltage connected low carbon technologies on power quality

B4 Impact of low voltage connected low carbon technologies on network utilisation

B5 Opportunities for smart optimisation of new heat and transport loads
Electrification of Heat and Transport

Report B1 [14] describes the Low Carbon London trials involving Electric Vehicles (EV), providing the description of the EV fleets and the network of public and private charging points covered by the trial. A detailed analysis of the data collected during the EV trial was conducted, in order to characterise the new EV demand by identifying the key requirements associated with EV charging including energy per vehicle, charging power, temporal charging patterns and diversity of EV demand. Key features of EV charging profiles are characterised for residential, commercial or public charging points. To our knowledge, the combination of charging data collected for residential and commercial vehicles, logging of driving patterns and monitoring of public charging stations constitutes one of the largest trials to date in Great Britain.

Electrification of road transport is becoming a prominent element of decarbonisation policy in the energy sector, accompanied with a high share of low-carbon electricity supplied by renewable generation and technologies such as nuclear and carbon capture and storage. A transport sector based on EVs would be characterised by significant flexibility in terms of when the vehicles charge, creating opportunities for utilising more efficient charging strategies to optimise electricity generation and enhance the efficient usage of network capacity. Unlike conventional vehicles, EVs offer their users the convenience of charging at home without the physical presence of the driver, although this comes at the cost of lower driving range and longer charging times.

The EV trials are described in LCL Report B1 [14]. The EV data collected in the LCL trial covered three broad areas: (i) metered EV charging data for 72 residential and 54 commercial charging points; (ii) data on charging events collected at 491 public charging points; and (iii) vehicle logger data capturing driving and charging behaviour for 30 EVs.

Key information recorded included active power for charging, timing and duration of charging events and the energy required by EVs during charge events. Residential EV trials have confirmed the assumptions made in previous studies that uncontrolled EV charging results in high
peaks that broadly coincide with the existing system peak demand, creating additional stress for the electricity system infrastructure. This occurred even in some cases when a tariff incentive was in place with the customer. The highest demand for residential EV charging is recorded between 6pm and midnight, with very low demand during night and early morning hours. The charging demand per vehicle, averaged across all days covered by the trial is about 3.5 kWh, which corresponds to around 17.5 km in distance travelled. This is slightly lower than assumed in previous studies for a nationally representative sample, which could be expected given that LCL EV trials took place in an urban environment characterised by shorter driving distances.

A major share of EV charging demand for the monitored residential and commercial vehicles was met through home charging posts for residential i.e. office charging points for commercial participants. Only 13% to 16% of charging events occurred at charging points other than these. The average observed duration of charging events was about 2 hours for residential and 3 hours for commercial vehicles, with only a small number of events taking more than 5-6 hours. The median distance associated with a single journey undertaken by both residential and commercial EVs and recorded by data loggers was around 3.5 km, while 95% of trips were shorter than 25 km and 20 km for the two groups, respectively.

A very regular diversity effect is observed for the charging demand of the residential EV sample, with diversified peak demand per vehicle at about 25% of the peak demand for an individual vehicle. This means that for a population of EVs of the size of the residential sample, each with a maximum charging power of 3.6 kW, the diversified peak to be used for calculating aggregate EV demand would be only 0.9 kW. For larger numbers of EVs the diversity factor converges to around 20%, while for a low number of vehicles connected to a common supply point (i.e. less than 10) this factor increases to 63% or more. Diversity considerations provide an important input into the network planning process.

Case studies conducted in Report B1 [14] based on vehicle logger data for residential EVs identified a significant potential for smart EV charging to support peak demand management, without affecting the capability of EV users to make their intended journeys. This suggests that implementing smart charging strategies will be crucial to ensure an efficient integration of EV demand into the existing electricity systems.

Energy requirements for commercial EVs are found to diverge significantly depending on the vehicle use. For pool and company vehicles the energy requirement was about 2.5 times lower than for residential, with about 1.4 kWh of electricity required daily (sufficient to cover about 7 km). Delivery fleets on the other hand required about 14 kWh per charging point and per day. The charging profile of the former subgroup peaks around 10am and then gradually tails off towards the end of business hours (6pm), while the charging patterns of delivery vans display a rapid increase in demand from virtually zero to about 2 kW per charging point between 3pm and 6pm on workdays. Despite the lower sample size in the pool and company car group (there were eventually only 16 vehicles with charging power data), there is again considerable diversity observed with respect to the peak demand observed – diversified peak per EV was about 30% of individual vehicle peak demand. The diversity factor for the 10 delivery vehicles included in the trial was much higher, about 86%, due to the high coincidence of charging across different charging points driven by shift work. This proves that the connection of different types of commercial users and their impact on planning network infrastructure will need to be considered taking into account their specific charging profiles, energy requirements and diversity characteristics.

The project monitored all of the available public charging stations in the Source London network when it commenced in 2013 (the number at the end of May 2014 stood at 1,408). It was found however that a significant number had zero charging events and so were discounted from the analysis. The data suggest that public stations were used rather infrequently, with great variations in charging duration and energy. The median usage frequency for a charging station was 5.5 times per month, and median number of charging events at these stations per EV was 3 over the trial period (16 months). Users generally relied on public charging stations for a small fraction of their daily distances travelled (median daily energy per EV was equivalent to 0.4 km per day). Peak electricity demand averaged across all stations was 0.1 kW, and the most intensive usage occurred between 12pm and 4pm. Energy demand during weekends was about 35% lower than on weekdays. Whilst public charging infrastructure is often quoted as a barrier or a pre-requisite for the uptake of electric vehicles, it is not yet being heavily used by existing early adopters in the London area.

Evidence on the use of EVs by trial participants represents an important breakthrough in terms of understanding the requirements of EV users, as this type of data has not been available previously in this form and on this scale. The trials carried out confirmed and verified the EV demand models previously used by the authors of Report B1 [14] that were based on nationally representative driving statistics for conventional vehicles. These models, calibrated using the LCL EV trial data, will therefore continue to be used in the later stages of the LCL project to investigate the opportunities for more efficient distribution network planning with smart EV charging, in particular in the LCL Report D3.
Trial data analysis has shown that the shape of the additional EV charging demand will depend on several critical factors, such as the number of vehicles involved, user type and day of the week. Understanding the expectations regarding the future uptake of EVs in a given distribution network therefore seems critical in order to appropriately plan for the projected demand increase in existing residential households and to meet new connections associated with public charge posts and organisations converting their fleet to electric vehicles. Updating the demand forecasts based on the expected EV uptake will thus facilitate making informed and appropriate infrastructure reinforcement decisions. The analysis carried out in Report B1 [14] can also provide a basis for assessing the diversity of aggregate EV demand depending on the expected evolution of EV penetration.

Given the potential to use the flexibility of EV demand to support network management, as illustrated in the case studies in Report B1, the value of different smart charging control approaches should be thoroughly understood and taken into consideration in distribution network operation and planning, along with the traditional reinforcement solutions available to network operators. Preliminary analysis presented in Report B1 shows a significant potential of smart EV charging to deliver savings in distribution infrastructure investment.

The analysis based on evidence gathered in the LCL EV trials has demonstrated there are significant opportunities for adopting smart charging approaches in order to ensure an efficient integration of electrified road transport, but also indicates segments in which this will not be needed for some time to come, such as the low-utilised public charging points. Potential benefits from smart charging schemes, backed by a substantial body of trial data, indicate that their implementation will be vital for enabling an efficient deployment of a high number of EVs in distribution grids.

3.1 Heat pumps and photovoltaics

Report B4 [18] focuses on the network impact of two key low carbon technologies that are being promoted by UK policy, namely Photo-Voltaic solar panels (PV) on domestic premises and domestic Heat Pumps (HP).

These technologies present opposing challenges to the distribution network: with PV there is the potential for over-voltage and back-feeding of power from the Low Voltage (LV) network onto the High Voltage (HV) network when local demand is low but PV generation is high; with HPs, the additional load at times of peak demand may cause thermal and voltage limits of infrastructure to be reached.
Table 6: Heat pump daily peak load increase at different average temperatures

<table>
<thead>
<tr>
<th>Scenario</th>
<th>5% penetration</th>
<th>10% penetration</th>
<th>15% penetration</th>
<th>20% penetration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1 (-4°C average)</td>
<td>19%</td>
<td>33%</td>
<td>48%</td>
<td>72%</td>
</tr>
<tr>
<td>Scenario 2 (0°C average)</td>
<td>9%</td>
<td>18%</td>
<td>32%</td>
<td>39%</td>
</tr>
<tr>
<td>Scenario 3 (4°C average)</td>
<td>9%</td>
<td>14%</td>
<td>18%</td>
<td>25%</td>
</tr>
<tr>
<td>Scenario 4 (7°C average)</td>
<td>5%</td>
<td>7%</td>
<td>11%</td>
<td>15%</td>
</tr>
</tbody>
</table>

For an average outdoor temperature of -4°C and a penetration level of 20% of households owning heat pumps, the peak daily load increased by 72% above baseline. As most heat pumps in the network will be working at full capacity in weather this cold, diversity will be greatly reduced. In addition, heat pumps work at reduced efficiency in low temperature conditions. These two factors are responsible for the large increase in peak load. In contrast, at 7°C the corresponding peak load increase was just 15%. Here diversity is increased and heat pump efficiency improved. Reducing penetration levels from 20% (to 15%, 10% and 5%), shows approximately proportional reductions in peak loading increase. Neither of UK Power Networks’ or the Department for Energy and Climate Change (DECC)’s forecasts are expected to reach penetration levels above 5% for the next decade, but from these early indications it would appear that tangible additional transformer headroom is required to account for cold conditions in which diversity is much reduced and the Coefficient of Performance (COP) of the heat pumps collapses, even at lower level of 5% uptake amongst domestic customers. This applies only in cases where an all-electric solution is being used (i.e. no residual back-up from gas central heating).

Table 7 summarises the findings from modelling the uptake of PV. Higher penetration levels of PVs in the network cause significant levels of back-feeding at the substation. At 30% penetration this reverse power flow was high enough for there to be almost zero net energy demand. Some over-voltage was seen at all penetration levels. At penetration levels which are currently forecast by UK Power Networks to reach around 5% over the next decade, over-voltages of the order of 2 volts may consistently arise unless voltage control regimes are adjusted. Whilst uptake at higher levels is not currently foreseen, it is interesting to examine the nature of the relationship between penetration and instances of over-voltage at higher uptake levels. At 25% penetration the over-voltage more than doubled to 4.3V, but from here onwards it rose steeply to 14V at a 30% penetration level. In practice, inverter cut-outs should prevent over-voltages of more than 9V.

Table 7: Summary of findings from PV modelling

<table>
<thead>
<tr>
<th>Penetration level:</th>
<th>5%</th>
<th>10%</th>
<th>15%</th>
<th>20%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Over-voltage</td>
<td>2V</td>
<td>3V</td>
<td>4.3V</td>
<td>14V</td>
</tr>
<tr>
<td>Reverse power- flow level</td>
<td>None</td>
<td>Low</td>
<td>High</td>
<td>High</td>
</tr>
</tbody>
</table>

PVs are in a sense a more benign technology, since if significant over-voltage occurs then they will temporarily cease generating. However, this is detrimental to customers who risk losing the income associated with the Feed-in Tariff. As indicated above, even modest penetrations of 5% PV may require voltage control regimes to be examined and adjusted over the next few years.

Heat pumps could present a more serious problem in that existing networks could be driven beyond thermal capacity with only a small percentage of homes using heat pumps for space heating, unless the network has been reinforced. In particularly cold conditions, the maximum demand for a typical home with heat pump technology can reach 4.5kW after diversity, with 3.6kW from the heat pump operating steady state. Above freezing temperatures the heat pump becomes increasingly benign to the system as well as being a lower carbon alternative to gas central heating.
3.2 Impact of LCTs on Power Quality

Report B3 [8] describes the results from trials, laboratory studies and modelling of the effect of Distributed Energy Resources (DER) on the power quality experienced on an LV feeder. The prime focus is the harmonic distortion aspect of power quality. Issues of voltage magnitude error are covered in report B4 “Impact of Low Voltage – connected low carbon technologies on network utilisation” [18] from the Low Carbon London project.

Three DER technologies were considered, heat pumps, solar photovoltaic inverters and electric vehicle chargers and all were considered within a residential context.

Twenty heat pump installations in a variety (and geographically dispersed) set of domestic dwellings were monitored with 18 yielding useful data. The current harmonics drawn across a normal operating pattern for a month were observed in average and peak form. Data for real and reactive power draw and local connection voltage were also gathered.

Laboratory testing of four individual PV inverters was conducted with current harmonics recorded as a function of the DC power provided from a controlled source taking the place of a PV panel. Multiple charging events of several electric vehicles were also recorded.

There was a clear difference between the harmonic distortion of the PV inverters on the one hand and the heat pumps on the other. The PV inverters exported largely sinusoidal current with relative low levels of low-order harmonic distortion compared to the heat pumps. For example, a PV inverter typically produces a mean 3rd harmonic current of less than 0.3 A whereas the heat pump devices had a mean 3rd harmonic current of up to 2.2 A.

The 18 sets of heat pump data showed a wide variation of levels of distortion between the devices. All are believed to comply with the EN 61000-3 standard for customer products but some are close to the harmonic limits for the low-order harmonics whereas others are far below and provide close to sinusoidal current. Specifically, the poorest example had a mean 3rd harmonic of 2.3A and a maximum THD of 200% and the best 0.25 A and maximum THD of 30 %. There was variation between brands, between products within a manufacturer’s range and between identical equipment in different dwellings. Some of the large differences are believed to stem from quite different types of compressor motor and motor control between product types. Some differences may arise between the same products in different households because of the different load cycle given that the harmonic distortion was seen to vary with loading. It is likely that the products with the highest harmonic distortion use either a diode rectifier and motor drive or a phase-angle control device (e.g. triac). Low-order harmonic distortion from such devices is synchronised to the mains waveform and appears at broadly similar phase angles for all devices and which accumulate in the network feeder. Higher order harmonics tend not to synchronise and add at random phase angles. The EV charging data also includes an example of high harmonic distortion (yet compliant with EN 61000-3) that would indicate a simple diode rectifier has been used.

The drawing of low-order harmonic currents at several points on a feeder that are phase aligned could lead to large harmonic voltage drops across feeder sections and substation transformers, and long neutral lines for some harmonics. The concern is that if large numbers of DER which are EN 61000-3 compliant but which draw significant harmonic current are present on a feeder, the combined effect could lead to harmonic voltage distortion could exceed the planning standard G5/4-1. Low-order harmonics are of particular concern because of their tendency to be synchronised between sources. G5/4-1 allows a maximum THD of 5% for the 400 V network and up to 4 % for the 3rd, 5th and 7th harmonic. For a 230 V phase, 4 % is only 9.2 V.

Electric vehicles and heat pumps (design depending) will convert the AC voltage to a DC voltage by the use of a diode rectifier. Household electrical loads do already include examples of diode rectifiers but these are for low power consumer electronics (radio, personal computers and game consoles). There are examples of phase-angle control of lighting, also at low power. Household loads of above 1kW have generally been restricted to heating loads (kettles, washing machines, showers etc.) which are linear loads which do not distort and, further, tend to damp harmonic voltage cause by other equipment. Thus at least some of the heat pumps examined and the EV chargers are a concern because these are distorting loads at much high levels of power and current.

To gain some insight into whether the concern is well founded, example feeders were simulated using the basic characteristics from substations that form part of the Low Carbon London study areas. Example feeders had up to 50 households connected in a similar pattern to real feeders. Two gauges feeder cable were examined: 95 mm² and 185 mm². Two sets of spacing of service joints were chosen to test dependence on cable impedance and results were repeated for the heat pumps with the highest and lowest harmonic distortion. Heat pumps were progressively installed on the feeder and levels of voltage distortion recorded. The test assumed all heat pumps running at full
power. Clearly, if some diversity in their operation can be assumed the results could be adjusted. It was found for the Queens Park feeder that for the most distorting heat pump, levels of voltage distortion exceed planning standard at around 20 heat pumps, a penetration of 40%. The exact number depends on the placement; here a random placement pattern was used.

The literature suggests that at penetrations of 20% other factors such as voltage limits or line flow are likely to be constrained. Results from the Queens Park feeder suggested that the voltage was outside of the limit for phase 1 after 10 heat pumps and for phase 2 after 36 heat pumps. There were 22 heat pumps on feeder 1, 17 heat pumps on feeder 2 and 11 on feeder 3. The voltage was outside of the limit for 20% penetration and 72% for feeders 1 and 2. This is an average of 42%. This result is slightly higher than what the literature suggests, however, the simulation did not consider the background load. This percentage will decrease as the background load increases.

The conclusion from the simulation was that the harmonic distortion is not likely to be the first constraint to be reached. The feeder voltage constraint is likely to be reached before the harmonic voltage distortion becomes an issue.

It is clear that there is not a single answer to the question of whether DER will cause power quality problems on LV feeders. Even among the relatively small number of cases examined, there are big differences in levels of harmonic current. The PV inverters were found to have low distortion, comparable with the best of the heat pumps and with a low likelihood of enough harmonic current flowing to on a feeder to cause problematic level of voltage distortion. However, the worst performing heat pumps and the one example EV charger do appear likely to cause problems when deployed in clusters, although there may well be other constraints which are met before the harmonic voltage constraint. If all of the devices rightly claim compliance with EN 61000-3 it will be difficult to assess a mixed deployment without detailed knowledge of the equipment concerned or use of a conservative worse-case assessment.

“We found that the residential EV charging peak is later than originally thought (9pm instead of 7pm), so is more manageable than we initially thought.”
Network Planning and Operation

The core functions of the Distribution Network Operators (DNOs) include forecasting future demand and generation from both the macro-economic and regional levels; planning appropriate capital investment programmes; carrying out detailed network design and planning in order to execute the capital investment plan or to respond to new connections; and operating the network and responding to faults on the network when they occur.

Underpinning all of these functions is visibility of how residential customers are using electricity, and how different customer segments in the industrial & commercial sector are managing their electricity use and in some cases generating or co-generating electricity on site. LCL established three areas in London in which it instrumented the network in order to understand active and reactive power flow per feeder. This also enabled a new application of state estimation to be tested and verified.

We have replaced many of the assumptions in our demand forecasting model with the new data from Low Carbon London, and which we believe will make our plans more accurate and avoid over- or under-investing. We estimate that there could be a 10TWh saving in electricity consumption by 2020 from energy efficiency measures, equivalent to approximately 8% of the projected domestic demand in 2020.

Finally, UK Power Networks recommends that DNOs consider adopting the voltage alert parameters and settings proposed by Low Carbon London when establishing their interface to Smart Meters.
C1 Use of smart meter information for network planning and operation
C2 Impact of energy efficient appliances on network utilisation
C3 Network impacts of energy efficiency at scale
C4 Network state estimation and optimal sensor placement
C5 Accessibility and validity of smart meter data
Network Planning and Operation

Report D1 presents an overview of the processes in the DNO business that will be informed by the key findings from the Low Carbon London project, from load forecasting, to planning and network operations. The project has identified how enhanced visibility provided both by monitoring and smart meters could potentially inform the management of a low carbon network with a significant uptake of low carbon technologies. It is therefore recommended that the key findings are adopted and considered in updating and adapting DNO planning and operation processes.

The future DNO will have more visibility than current practices; the trials have highlighted the importance of data management and have informed the business of how best to interpret more visibility data on the network. With high LCT uptake, having more visibility will be key for DNOs to react accordingly and plan the network to meet customers’ requirements within operating standards.

Until now DNOs have used conservative approaches and theoretical data on potential impact of LCTs. LCL has now provided DNOs with empirical data to inform the forecasting process. The real profiles of LCTs, described in Report B2, will not only be useful for forecasting impact but will be able to update the industry’s modelling tools. Also, using the diversity curves derived from the LCL trials, DNOs can reduce the uncertainty around diversity and LCT uptake.

Smart meter data will also provide visibility which may enable DNOs to both plan and operate the networks more efficiently. Historically, planning the network has been based on static load profiles and planners have designed the network with a conservative approach to ensure adequate security of supply. Smart meter data can also be used in a bottom up approach to provide visibility of the capacity and demand, particularly on the LV network. This will be critical when LCTs, and specifically heat pumps, are connected at volumes high enough to increase the maximum demand on the network during specific periods of the year.
The difference in the demand profiles identified in Report C1, by ACORN group, presents an opportunity for DNOs to design networks and new connections with a consideration for the demographics of the consumers in mind. Taking this into account, using relevant indicators of both occupancy and economic factors, will enhance the accuracy of forecast peak demand and reduce redundancy in installing underutilised assets.

An adapted version of the load forecast model is to be developed following Low Carbon London, to incorporate the nine consumer types identified from the LCL trials which are to be used in place of the previous consumer types. The LCL consumer types are represented by individual profiles (profile shape and annual consumption). Furthermore, these domestic profiles are affected by future energy savings specific to each of the nine profiles across various appliance categories (dependent on their appliance ownership characteristics as understood from the LCL appliance ownership data).

Analysis in Report D1 highlights that whilst aggregation will ensure data remains private it is important to consider that if levels of aggregation are high, the DNO will lose some elements of visibility which may have be useful in managing the network. It is anticipated that this effect could be more prominent in rural networks due to the lower density of customers connected to local substations.

The LCL trials have proved that DSR is a flexible resource that can be considered by DNOs to optimise network use and manage demand without having to reinforce the network. In the planning function, DSR can be used to defer the investment requirement and support planned outages on areas of the network that are suitable. To support this, LCL has developed a methodology for site selection as well as a tool to help DNOs measure the impact of a potential DSR contract, taking into account the commercial restrictions of the contract, the reliability of the service based on the specific technology or type of customer, and the substation load profile. In the case of Network Operations, DSR has been highlighted as useful tool in the support of unplanned outage events on the network, where demand on the network can be curtailed in order to ensure that the appropriate capacity is in place to safely manage other load on the network and to maintain compliance with security of supply regulation P2/6.

Similarly in the Networks Operations function, smart meter data presents benefits and opportunities as well as potential challenges. For example, the DNO will be able to detect domestic outages without relying on customers calling in. Furthermore, the ability to set voltage alerts with smart meters will be extremely useful to DNOs when managing voltage issues on the network. Analysis has shown that the voltage settings of the smart meters will be a key factor when balancing the number of alerts with the actual value of the information provided by these alerts. Sensitivity analysis developed on the real voltage data from the LCL Engineering Instrumentation Zones has shown how the duration of the voltage alerts can be useful to determine the real voltage problems in the network. Voltage management processes within DNOs will have to change significantly to consider the data provided by the smart meters and accurately manage any voltage issue on the network.

Finally, to incorporate all the findings from this report, DNOs must ensure that the adequate and ad-hoc IT systems and processes are fit for purpose and integrated. As more smart solutions are implemented on the network it will be increasingly important to set up clear feedback loops in order to update forecasting processes with the effectiveness of the smart solutions.

### 4.1 Network state estimation

Report C4 [17] analyses the performance and presents potential benefits of the application of Distribution System State Estimation (DSSE). Measurements carried out within Engineering Instrumentation Zones (EIZs) of Low Carbon London (LCL) demonstrate that the developed prototype DSSE, through a limited number of optimally placed sensors could robustly estimate voltage and power flows in High Voltage (HV) distribution networks. This work presents one of the pioneering efforts in examining the role and possible application of DSSE in the present and future distribution networks in the UK.

In contrast to the national transmission system, where measurements are widely deployed to provide visibility and support to the real-time control of the transmission system, available measurement infrastructure in HV distribution networks is not sufficient to facilitate real time control, essential for the evolution to the smart-grid paradigm. Thus additional measurements in distribution networks, of appropriate type and location, will need to be established to support the implementation of innovative real time active distribution network management practices necessary to facilitate cost effective integration of low carbon demand and generation technologies in distribution networks.

As the number of distribution network assets is far greater than the number of assets in the transmission system, it becomes clear that full instrumentation of the entire distribution network may not be justified economically. Hence the challenge is to identify the volume of measurements of appropriate types and locations,
to be able to establish the state of the system ("network observability") across different network operating conditions with adequate accuracy. This work demonstrates that DSSE techniques can minimise investment associated with the deployment of measurement infrastructure whilst maximising the network observability and confidence levels in network voltage and power flow profiles, as well as providing the ability to detect and isolate inaccurate measurements.

The scope of our studies includes the following:

- Development of DSSE model to enhance network observability through estimating network voltage and power flows for a balanced HV distribution network;
- Application of DSSE to determine the optimal number and locations of new sensors;
- Analysis on the application of DSSE to estimate voltage and active and reactive power flows for peak demand condition on the selected Engineering Instrumentation Zones feeders including feeders BRXB-SE3, and BRXB-NE2 from Brixton EIZ, feeder MERT-E2 from Merton EIZ, and feeder AMBL-NW1 from Queen’s Park EIZ;
- Rigorous testing of DSSE model and analysis on the accuracy and robustness of voltage and power flow estimates using half-hourly data across one year;
- Development of an approach to detect bad data and the use of pseudo measurements as alternative for the missing real measurement data; and
- Meter placement studies along the selected EIZ feeders.

Comprehensive sensitivity analyses have also been carried out to assess the impact of uncertainty in the accuracy of the measurements and network parameter data on establishing the state of the system across large number of different network operating conditions.

The key findings from this study can be summarised as follows:

- The DSSE in combination with limited number of sensors and more extensive use of pseudo-measurements is a robust tool for improving the observability of distribution networks, which is increasingly relevant for the present distribution system and critical for the operation of future smart-grid. The DSSE can bring benefits across a number of relevant areas:
  - Improve observability in part of the network where the real measurements are not present; there are conditions where new measurements cannot be installed due to space restriction in the substations, especially underground substations;
  - Identify faulty measurements, or temporarily bad data due to recording or communication failures for example, so that the bad quality data can be isolated to improve the overall quality of estimation;
  - Improve the accuracy of the measurements as DSSE takes into account data from all measurements and therefore is able to correct errors from individual measurements;
  - By improving network observability, DSSE could enhance real time distribution network operation activities that may involve network reconfiguration and restoration, support asset management, inform network planning and network pricing; and
  - Carry out general assessment of the meter performances, identifying those that should be replaced.

- The proposed and developed meter placement methodology in EIZs is robust and its applications have been demonstrated. We have demonstrated in the meter placement studies, that placing 2 or 3 meters have significantly improved the network visibility.

- Our studies suggest that the uncertainty (error margin) of the estimated voltages is relatively small and in most of the cases, the error margin is less than 0.22% (in comparison to the error margin of individual meters: 0.3%-0.6%). We demonstrate that the materiality of the accuracy of power flow estimates will be driven by the capacity/rating of network. The use of DSSE can also enhance network visibility for the lateral sections where the substations may have no measurements installed.

- The way in which the available network data is recorded and stored in the Distribution Network Operator’s (DNO’s) database can affect the effectiveness and accuracy of DSSE. For example:
  - Some network databases only provide information associated with the first section of the HV feeders, although the rest of the sections could involve cables of different types, having different electrical characteristics. The impedances of the line connecting two nodes are calculated according to the first segment of the feeder which may introduce error in the network parameters and eventually in the DSSE calculations;
  - Time synchronisation in taking the measurement samples at different measurement locations is very important for the implementation and application of DSSE. As the system states change dynamically, by using non-synchronous measurement data for the
calculation of DSSE increases the error margin of the DSSE output. This is an area that will require further development; and

- Bad data and missing data during some time periods can additionally contribute to the inaccuracy of DSSE.

- Unlike in the transmission system where the loading across different phases is balanced, the level of imbalance in distribution network can be large, which would reduce the accuracy of the DSSE which assumes that the system is balanced.

- Further work will be required to quantify the economic benefits of the application of DSSE in distribution networks, although it can be preliminary concluded from our studies that the implementation of DSSE will have positive impacts on DNO business activities, e.g. daily operation, planning, asset management, safety and network pricing activities. The benefits of DSSE in reducing the number of measurements required also provide strong business cases for its implementation.

4.1.1 Recommendations

Based on the experience gained in this project, we list a set of recommendations that will assist implementation and application of DSSE in distribution networks. The implementation of DSSE as an integral part of the DMS monitoring system will enhance the capability of the distribution network operator to make informed operation decisions so that the network can be operated securely while making full use available network capacity. To start with, it is recommended that DSSE is employed in stressed parts of distribution networks that are operated close to the operating voltage and/or thermal limits, and then be subject to close monitoring. In order to facilitate the application of DSSE, additional measurements may need to be installed. The approach described in Report C4 [17] can be used to determine the locations and types of measurements needed. Enhancing system state visibility will also benefit network planners, as they can identify the changes in the utilisation patterns and devise optimal strategy for network reinforcement, based on the information gathered from the monitoring system.

It is important to highlight that the main barriers for effective implementation of state estimation lie in the availability and quality of network data. Improvement and standardisation of measurement and recording practice, as well as further enhancement of the DSSE algorithm will contribute to more effective and efficient distribution network system monitoring and control. In this context, our recommendations can be summarised as follows:

- Synchronising readings of all measurement points;
- Improving the availability of key measurements. For example, some of the important measurements are those at the beginning of each feeder, making them available and avoiding the need for pseudo measurements could crucially improve the estimation;
- Checking the accuracy of the recorded network parameters (especially the ones that consist of multiple cables) and the accuracy of recorded transformer winding ratios and the tap-changing positions;
- Validating the measurements accuracy of the sensors in the key feeders where the DSSE is to be applied for operational purposes, as the sensor accuracy is a key factor affecting the outcome of the DSSE. A robust procedure of Remote Terminal Units (RTUs) installation and commissioning needs to be implemented;
- The use of typical load profiles of connected customers in the applications of pseudo-measurements for unmonitored substations is recommended, since it can significantly improve the accuracy of the DSSE model;
- In most cases, placing measurements at feeder supply point at primary substation and towards the end of important feeder branches would enhance the accuracy of voltage estimation and enhance bad data detection;
- As the network imbalance impacts the accuracy of State Estimation (SE), it may be appropriate to consider developing DSSE specifically for unbalanced three phase networks. The application of techniques for improving phase balance, that would reduce network losses and enhance the utilisation of LV and HV networks, would also enhance the accuracy of state estimation;
- A further theoretical development of DSSE, meter placement techniques and algorithms could also be undertaken to develop capabilities addressing network re-configurations on a smartly controlled distribution system environment; and
- Carrying out comprehensive studies analysing and quantifying in more detail the cost and benefits for rolling out the applications of DSSE and to establish standards for its implementation.
In future DNOs are likely to play a far more active role in managing load and generation on the network than is currently the case today, and will need to have a wider range of commercial relationships with other partners both within and outside the traditional energy chain. The LCL project has demonstrated these new organisational relationships, and demonstrated that these can be achieved within the current industry structure. Specifically, LCL has demonstrated commercial relationships with four energy aggregators and bilateral arrangements with 37 demand response sites; control room integration with two demand response sites; system integration with a Charging Network Operator (CNO) in order to call off demand response from electric vehicle charge posts; and a shared or multi-purpose Time-of-Use tariff with one of the major energy suppliers (EDF Energy).

The project has also clearly demonstrated areas in which closer inter-working will be required in the future, either within the same or any modified industry structure. Over the next decade, DNOs will be procuring DSR as a new entrant alongside the largest single procurer today, the Great Britain System Operator (GBSO), National Grid. By the mid-2020s, modelling carried out within LCL suggests that energy suppliers will be an equally significant player as the GBSO is today, as they seek to balance a much larger proportion of renewable generation within the generation fleet.

Whilst electric vehicles and heat pumps are themselves carbon-saving, the project has for the first time calculated the additional carbon benefit of supporting these technologies with ‘Smart’ networks as opposed to traditional networks.
Development of new network design and operation practices

DNO tools and systems learning

Design and real-time control of smart distribution networks

Resilience performance of smart distribution networks

Novel commercial arrangements for smart distribution networks

Carbon impact for smart distribution networks
This chapter takes the results of chapter 3 assessing individual LCTs and considers how they might impact distribution networks when combined and connected to the networks at increasing penetration levels.

5.1 Network operation

5.1.1 Multi-period analysis of the contribution of LCTs to distribution network operation

Report D3 [15] analysed the state-of-the-art of the emerging advanced distribution network operation and control applications, which are critical for facilitating efficient integration of distributed Low Carbon Technologies (LCTs) trialled in Low Carbon London project including controllable Industrial and Commercial generation-led and demand-led Demand Side Response (DSR), Electric Vehicles and Heat Pumps and Domestic dynamic Time-of-Use tariff to facilitate efficient operation and investment of distribution networks and provide support to the national transmission and generation system. Active management of distribution networks could generate significant savings in network cost when accommodating new types of load and distributed generation, which are expected to considerably outweigh the cost of the implementation of active paradigm.

The main topics addressed in the report include: (1) applications of controllable Industrial and Commercial demand-led DSR for peak demand reduction; and (2) control of smart Electric Vehicle, Heat Pumps, controllable I&C DSR, and dToU-based DSR, by employing a multi-period AC OPF tool (TimeOPF).

In order to use demand-led DSR resources with load recovery characteristics for efficient peak reduction, they will need to be controlled hours before and after the onset of system peak conditions. Ignoring the energy payback requirements and other DSR limitations may result in suboptimal operating strategies or even increase the peak above the pre-intervention case.
This would also require that in order to achieve a given peak demand reduction the volume of DSR response to be contracted (ignoring any non-responsiveness, compliance and timeliness issues) would generally need to be a multiple of the targeted peak reduction, depending on the DSR penetration, shape of demand profile and their response/payback characteristics (duration of control and payback periods, payback power and energy), as illustrated in Figure 17. Using I&C DSR for peak management requires that the network analysis and operation planning are done in a multi-period timeframe, rather than based on snapshots in time, given the temporal links between DSR control decisions in one period and their impact on the resulting demand profile several hours later.

![Figure 17: Peak reduction capability for different DSR response profiles (contracted volume = 100 kW) (Source: LCL Report D3).](image)

We further use the TimeOPF tool to perform multi-period optimisation of operating decisions of smart EVs, HPs, dToU and I&C DSR with the objective of relieving line congestions, manage voltage issues and support substation congestion management. To that end, Figure 18 shows the situation where one of the primary transformers in the Merton substation is on outage, limiting the allowed loading of the remaining 3 transformers to about 60 MVA. Without smart network management the substation loading would significantly exceed the transformer rating for more than 5 hours during peak load conditions, potentially requiring very costly demand curtailment. This is particularly relevant in the context of accelerated electrification of heating and transport demand, as these demand categories would likely increase peak demand proportionally much more than the energy required from the network. If on the other hand smart DSR technologies contribute to network operation, a significant portion of demand can be shifted to time periods when the network is less stressed, enabling the total loading to remain within the allowed limit. The flexibility parameters associated with different DSR technologies are predominantly based on the findings of LCL trials.
By using LCL trial data, we demonstrate the importance of multi-period DSR scheduling for an efficient support to network operation and reducing peak demand. We find that the multi-period analysis is crucial for an adequate assessment of DSR capabilities to support network operation and resolve thermal and voltage issues, given that efficient peak demand management requires DSR control hours before and after the peak occurs.

The studies also clearly show that peak management schemes should be carefully designed in order to avoid an outcome that is even worse than without any DSR control, i.e. should consider the fact that DSR control will have an impact on electricity demand in later subsequent periods due to the payback effect or load recovery. By scheduling DSR operation while respecting the user-driven restrictions (e.g. when they need to use their vehicles or what indoor temperature levels they need to maintain), it is possible to avoid a range of issues associated with network management and potentially avoid or postpone the need to reinforce the network. Our studies have shown that DSR technologies could be used effectively for network congestion management as well as voltage constraint management in distribution networks, potentially representing an alternative to conventional means of dealing with network management issues.

5.2 Network planning

5.2.1 Load related expenditure growth for the LPN distribution network

In Report D3 [15], the design of smart distribution networks is considered. Imperial College London’s Load Related Expenditure (LRE) model is applied to data from LCL to determine the potential savings in reinforcements of the London distribution network that may be achieved through application of smart demand control and energy efficiency measures. The time horizon from 2015 to 2050 is considered. This included analysis of the gross benefits of smart control of EVs and HPs, the roll out of dToU tariffs, I&C DSR and the uptake of energy efficiency measures. The gross benefits of the chosen LCTs are found by comparing the quantity and cost of reinforcement in a reference case with the quantity and cost of reinforcement when LCTs are applied.

The following scenarios are considered in the LRE studies and presented here. The first scenario is ‘smart electrification of the heat and transport sectors’ with three sub-scenarios: ‘smart control of EV charging’, ‘smart control of HP operation’, ‘combined smart control of EV charging and HP operation’. The second scenario is ‘deployment of dToU, I&C DSR and energy efficiency measures’ with four sub-scenarios: ‘use of a dToU tariff’, ‘use of I & C demand-led DSR’, ‘efficiency (high and low uptake)’ and ‘combined dToU, I & C demand-led DSR and a high uptake of efficiency’. The final scenario was ‘combined impact of all mitigation measures (Full Smart) compared with the above combined scenarios’ with sub-scenarios: ‘combined smart control of EV charging and HP operation’ and ‘combined dToU, I&C demand-led DSR and a high uptake of efficiency’.

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4 Low uptake of energy efficiency (referred to as “Efficiency 2050” in the figures) assume a linear uptake of efficiency by domestic and I&C consumers, reaching the level of 10% peak reduction in 2050. High uptake (“Efficiency 2025”) on the other hand assumes that the efficiency increases linearly until reaching 10% peak reduction in 2025 and remains at 10% until 2050.
Figure 19 shows the breakdown of economic benefits of the first set of scenarios (electrification of the heat and transport sectors). The gross benefit breakdown is given per asset type and per constraint.

**Figure 19: Economic benefits of smart HP and EV control (Source: LCL Report D3).**

The range of gross benefit is from about £50m by 2025 to about £850m by 2050. The majority of gross benefit is derived in avoiding reinforcement in the HV and LV networks with the highest benefit achieved by avoiding HV network reinforcement due to violation of thermal constraints.

Figure 20 shows the breakdown of economic benefits of the set of scenarios without electrification of the heat and transport sectors.

**Figure 20: Benefits of mitigation measures (Source: LCL Report D3).**

It can be seen that the cumulative benefit is between £70m for the ‘Efficiency 2025’ scenario in 2025 and £770m for the combined scenario in 2050. The majority of avoided reinforcement is in the LV and HV networks, amounting to about £600m for the combined scenario in 2050. It can be seen that about £155m is due to voltage constraints in the LV networks.
Figure 21 shows the breakdown of economic benefits of the ‘Full Smart’ scenario with comparison of the combined scenarios described above.

Figure 21: Benefits of combined mitigation measures (Source: LCL Report D3).

The Potential gross benefit in the ‘Full Smart’ scenario is between about £280m in 2025 and about £1,400m in 2050. The majority of saved reinforcement is in the LV and HV networks, amounting to about £1,000m for the ‘Full Smart’ scenario in 2050. It should be noted that the figures shown in section 5.2.1 above, are gross benefits and do not take into account the costs of implementing ‘smart’ responses such as ToU, both in terms of cost of supporting technology and cost of customer incentives.

5.2.2 Planning under uncertainty

Report D3 [15] explores planning under uncertainty. Here, using data from the LCL trials, we examine the additional value of DSR when it is used to provide the flexibility needed to deal with uncertainty. The greatest challenge in realising the transition to a low carbon smart grid in a cost-efficient manner, is the increased uncertainty that surrounds future generation and demand developments. There are three main classes of decision criteria when facing uncertainty; stochastic (also known as probabilistic), risk-constrained and robust. Stochastic planning is the case where each scenario node is attributed a probability of occurrence; the planner’s objective is the minimization of the expected system cost over all realisations. This approach can be made ‘risk-constrained’ by means of risk metrics such as expected shortfall (also known as ‘conditional value-at-risk’). Robust decision methods fall into two categories: optimisation against uncertainty intervals and use of the regret concept (min-max regret, for example, which identifies the optimal planning strategy so as to minimize a planner’s worst-case regret [16]). In this part of the report we focus on stochastic planning and min-max regret.

5.2.2.1 Option value of demand side response

Deterministic flexible investment options such as DSR possess significant option value due to their ability to defer and/or avoid premature commitment to capital projects by taking advantage of the inter-temporal resolution of uncertainty. Although DSR may not be the optimal choice under all scenarios, the ability for its contingent deployment can render ‘wait-and-see’ strategies, which could be deemed unattractive in the absence of cost-efficient interim measure, viable. On the other hand, deterministic approaches assume a perfect knowledge of the future and will tend to favor large-scale projects that enjoy scale economies. Deterministic planners do not opt for an interim solutions since they consider the future fully known and there is no case for deferring investment to offset stranding risk. It follows that suitable non-deterministic valuation investment decision frameworks are necessary to uncover this option value. Otherwise, the adoption of traditional non-flexible valuation methods such as NPV-based investment decision-making can systematically favour large-scale capital projects that may lack the necessary flexibility to enable the adoption of a ‘wait-and-see’ approach, thus unduly exposing planners to stranding and over-commitment risks.
To this end, stochastic programming is a generic framework for describing decision problems under uncertainty. Although there are numerous variants of stochastic problems, of most interest to long-term planning problems is the application using scenario trees, where the evolution of uncertain parameters is modelled in a discrete-time manner. A scenario tree is a coherent representation of possible future realizations of uncertainty. It comprises of scenario tree nodes that encapsulate possible states of the uncertain parameters at different times and arcs that capture the possible evolution paths. The main motivation for using this approach is the capability of capturing the planner’s decision flexibility. The concept of DSR option value is illustrated via a case study regarding the upgrading of a substation while planners face uncertainty with respect to future developments of peak demand, as shown in Figure 22. Planners can choose between investing in a new transformer and implementing a DSR contract.

**Figure 22.** Distribution system under study (left) and scenario tree depicting future demand developments (right) (Source: LCL Report D3).

We first present the optimal investment plan obtained when adopting a naïve deterministic approach where the DNO considers only the most probable scenario i.e. high-growth S1.

**Figure 23.** Optimal investment plan when planners can build only conventional assets (Source: LCL Report D3).

As can be seen above, the optimal plan involves investment in an extra transformer for £605k. Note that this commitment is undertaken from the very first stage to ensure that the asset is commissioned by 2016, so as to cover the foreseen peak demand which already exceeds the capabilities of the present system. It is worth highlighting that there is no value in considering a DSR contract. Although DSR could cover system needs up to 2017, a transformer would need to be constructed for subsequent years. As a result, DSR is not a cost-efficient solution for this particular scenario. Next, we utilize a stochastic decision framework and identify the optimal investment strategy, shown in Figure 24.
Figure 24. Optimal investment strategy when planners can build both conventional and DSR assets (Source: LCL Report D3).

As can be seen above, when considering alternative scenario realizations, the optimal investment strategy is radically different. First and foremost, there is no longer a ‘here-and-now’ decision to be made; the planner has adopted a ‘wait-and-see’ strategy towards first-stage capital commitments, meaning that it makes economic sense to not make any investment from the very first stage but rather wait for the resolution of uncertainty that occurs later to make more informed decisions. By further analysis the DSR option value is calculated to be £170k. In general, option value can be interpreted as the sum the planner would be willing to pay in order to gain the option of investing in DSR. Through further sensitivity case studies we also explore option value robustness by altering different parameters such as investment cost, DSR availability and discount rate.

In conclusion, we show that flexible investment options such as DSR possess significant option value and the use of traditional deterministic decision frameworks may systematically undermine their value.

5.2.2.2 Risk-constrained distribution network planning under uncertainty

To investigate risk-constrained distribution planning under uncertainty, a min-max regret approach for network planning under uncertainty has been developed, identifying robust solutions (including conventional reinforcement and DSR deployment) by minimising the maximum (across all scenarios) regret that the DNO will feel after the materialisation of the uncertain future. The regret felt by the DNO if scenario i is materialised, represents the extra cost that the DNO will incur due to the impact of uncertainty, with respect to the cost they would incur if they had acted according to the deterministic plan corresponding to scenario i. This approach is fundamentally different from stochastic optimisation approaches minimising the expected total cost total cost under the “weighted average” future materialisation.

Essentially, the min-max regret approach optimally balances two sources of risk: (1) the risk of stranded assets, encountered when more network capacity than the one that will be actually required in the uncertain future is procured and (2) the risk of incurring fixed reinforcement costs twice, encountered when less network capacity than the one that will be actually required in the uncertain future is procured.

Employing this min-max regret approach, case studies are carried out on a LCL network with 12 commercial buildings with demand-led DSR, participating in the LCL trials, considered as candidate sites for DSR deployment, and uncertainty associated
with the demand growth. Results indicate that the min-max regret approach adopts network reinforcement / DSR deployment actions that are not adopted by any of the deterministic solutions corresponding to the individual considered scenarios, and leads to significant improvement in the regret portfolio (Figure 25).

**Figure 25. Regret portfolio of different plans (Source: LCL Report D3).**

Furthermore, the case studies clearly demonstrate the value of DSR in providing flexibility against uncertainty. Specifically, DSR is shown to postpone capital-intensive network reinforcement until more information about the future evolution of uncertain parameters is gained and thus reducing the maximum regret felt by the DNO; this maximum regret reduction is higher as the cost of DSR deployment reduces (Figure 26), where CDSR denotes the cost of DSR deployment per site. The number of candidate sites selected for DSR deployment is shown to be bigger under the min-max regret approach than under deterministic planning, highlighting the significance of flexibility offered by DSR.

These results highlight the need for a new regulatory framework enabling the deployment of planning solutions that might not be cost effective under the traditional deterministic planning paradigm, but offer flexibility to deal with the undeniable uncertainty regarding temporal and locational evolution of demand growth and distributed generation penetration and reduce the resulting risks of capital-intensive planning decisions. The recognition of the value of DSR in that respect constitutes a major aspect of this new regulatory framework, as it can be deployed as an interim solution until information is gained regarding these uncertain parameters. Recognising this value stream will further contribute to the development of a viable business plan for DSR solutions.
5.2.3 Managing synergies and conflicts of DSR application in planning of future distribution networks

Historically, the development of distribution networks is decoupled from the development of other sectors in power system industries. This has been appropriate as the task of balancing of demand and supply at the national level has been carried out for conventional generation only.

Efficient real-time demand-supply balancing with a significant penetration of intermittent wind power and increased contribution from less flexible low carbon generation will become a major challenge. In this context generation-led and demand-led Demand Side Response (DSR) may provide increasingly more valuable balancing services to support the efficient operation of national electricity system and there may be hence growing conflicts between local and national objectives.

In general, it is widely acknowledged that generation-led and demand-led DSR, distributed energy storage and other emerging technologies could bring significant benefits to several sectors of the electricity industry, including distribution networks, transmission networks and generation system operation and investment. However, the energy supply sector and energy transport sectors (distribution and transmission networks) are operated by different entities and their level of integration and coordination is limited currently. Hence, the application of flexible DSR technologies to enhance the operation and investment performance of distribution networks, from the perspective of Distribution Network Operator (DNO) or to dedicate DSR to support system balancing at the national level may be suboptimal when considering wider national objectives. Managing the synergies and conflicts between distribution network, energy supply, transmission network, and the EU interconnection objectives when allocating DSR flexibility, may be critical for optimal development of the GB system as a whole.

Based on DSR flexibility trialled and demonstrated in Low Carbon London project, a number of studies have been carried out to investigate and quantify the role and value of multi DSR applications using the whole system approach (WeSIM). This framework allows holistic assessment of the value of DSR in reducing the system operational cost (by reducing wind power curtailment and maximising the utilisation of other low carbon generators) as well as reducing the infrastructure cost including the capital cost in low carbon generation needed to achieve particular CO2 target, network assets both at both transmission and distribution levels. The studies based on the GreenWorld 2030 scenario were carried out on a model that includes a representation of the simplified electricity systems of GB, Ireland and continental Europe.

The results in Figure 27 demonstrate that the whole system approach may lead to larger investment in distribution networks compared to the one obtained when using DSR to minimise distribution network investment (a DNO centric approach). This additional distribution network investment enables the flexibility of DSR to reduce primarily the operating cost and corresponding generation Capital Expenditure (CAPEX) needed to maintain the CO2 performance of the system, which is particularly relevant in the scenario with high penetration of variable renewables, inflexible generation system accompanied with low levels of interconnection with EU.

5 “Understanding the Balancing Challenge”, Report to DECC 2012 by Imperial College London and NERA.
6 Whole electricity System Investment Model, developed by Imperial College London.
The results also demonstrate that in the system characterised by inflexible generation and low levels of interconnection, the amount of investment in London distribution network should be higher to allow DSR flexibility embedded in the distribution network to support system balancing requirement by following the wind output, and hence reduce the wind curtailment and corresponding investment in low carbon generation in order to maintain the CO2 target. On the other hand, in case that the system is characterised by flexible generation and high level of interconnection with EU, balancing of demand and supply can be supported by large scale generation, and hence embedded DSR resources should be primarily used to manage peaks in London distribution network, and support balancing of demand and supply at the national level only when this activity does not conflict with distribution network constraint management objectives. This demonstrates that the level of flexibility available at national level, may impact distribution network planning, which will be driven by optimising the role of DSR flexibility to maximise the overall system benefits, considering both local and national level requirements simultaneously.

Furthermore, consideration of network losses in network planning clearly demonstrates the importance of shifting from the present peak demand and minimum network asset based design / reinforcement philosophy to a loss-inclusive network planning approach in order minimise the total system costs. The studies clearly show that increasing the LV and HV network ratings significantly beyond peak demand requirements will be optimal when considering benefits from reducing losses over the lifetime of the network assets.

From these studies, it can be concluded that managing the synergies and conflicts between distribution network, energy supply, transmission network, and the EU interconnection objectives when allocating DSR flexibility and planning distribution networks, will be growing in importance to facilitate the optimal development of the GB system as a whole. Silo approach e.g. DNO centric or Supplier centric perspective, may be suboptimal. Whole-systems approach joining energy, emissions and loss inclusive distribution network design is needed as present peak driven approach to distribution network design may lead to inefficient system operation and drive unnecessary additional investment in low carbon generation to deliver CO2 targets.
5.3 Reduction of carbon impact

Rapid expansion of Renewable Energy Sources (RES) and in particular wind is one of the key vehicles to enable electricity system decarbonisation. However, high penetration of intermittent wind generation will increase the requirements for reserve and frequency regulation services. Providing these services by part-loaded or fast-start plants (i.e. using the traditional approach) will both reduce the system operational efficiency as well as limit the ability of the system to accommodate RES, leading to reduced carbon benefits and increased balancing cost. These challenges present significant future opportunities for flexible service providers such as Demand-Side Response (DSR).

In this context, this report analyses and quantifies the implications of Low-Carbon Technologies (LCTs) and solutions studied in Low Carbon London trials for the carbon emissions and wind integration cost of the broader UK electricity system. Key findings of previous LCL reports, in particular those characterising the demand profiles associated with Electric Vehicle (EV) deployment, Heat Pumps (HPs), Industrial and Commercial (I&C) DSR, dynamic Time-of-Use (dToU) tariffs and energy-efficient and smart domestic appliances, are translated into nationally representative demand profiles and their impact on the CO₂ performance and wind integration cost of the electricity system is quantified using an advanced analytical model across three proposed scenarios covering the electricity system of Great Britain in the 2030-2050 horizon.

Given that the uncertainty of intermittent renewable output is expected to be a major driver for escalating integration cost, the performance of the system is analysed using Imperial College London’s Advanced Stochastic Unit Commitment (ASUC) model that is able to dynamically allocate spinning and standing reserve depending on the conditions in the system. As the ASUC model is also capable of considering system inertia and frequency response, it will be further able to investigate the impact of the provision of ancillary services from alternative sources on the carbon performance and wind integration cost of the system.

The results of the analysis suggest that LCTs are able to deliver significant carbon reductions primarily by enabling the future, largely decarbonised electricity system to operate more efficiently. Carbon benefits of different DSR technologies are found to be in the range of 50-200 g/kWh of flexible demand, and are a function of the assumed flexibility to shift demand and provide frequency regulation. Provision of frequency response in addition to smart balancing significantly increases the carbon benefits of all LCTs, and the greatest overall system-level reduction is observed in cases where all smart DSR technologies operate simultaneously in the system.

Figure 28 shows how the overall system emissions change with the deployment of smart LCTs, for each of the three analysed scenarios (2030 SP – Slow Progression, 2030 GW – Green World, 2050 HR – High Renewables).

**Figure 28. System emissions benefits across different years and scenarios (Source: LCL Report D6).**
Carbon benefits of LCTs are generally more pronounced in systems i.e. scenarios with higher intermittent RES penetration, although there are limits to this trend in case the non-renewable generation capacity on the system is also low- or zero-carbon (as in the 2050 HR scenario). Finally, we find that the integration of electrified transport and heating demand seems to be significantly less carbon intensive if smart operation strategies are adopted, making a more positive impact on the overall carbon performance of the economy.

The second set of study focused on the potential of DSR technologies to support cost-efficient wind integration by reducing:

- Wind balancing cost;
- Cost of required back-up generation capacity; and
- Cost of replacing curtailed wind output with an alternative low-carbon technology to achieve the same emission target.

Case studies presented in the report demonstrate that smart DSR technologies are capable of supporting cost-efficient decarbonisation of future electricity system by reducing wind integration cost. Penetration of individual DSR technologies i.e. the uptake of e.g. EVs, HPs etc. is a critical factor for the value of DSR for wind integration, as it determines the volume of flexible system services that can be provided by DSR technologies.

Average wind integration benefits when all smart LCTs coexist in the system vary between £6.4 and £11.4/MWh of absorbed wind output across the three scenarios. As illustrated in Figure 29, marginal wind integration benefit found in our studies is 2-3 times higher than the average benefit, suggesting an even more important role for DSR in supporting the expansion of wind capacity beyond the already high shares foreseen in future scenarios.

**Figure 29. Average (left) and marginal (right) wind integration benefits from deployment of smart LCTs (Source: LCL Report D6).**

5.4 Network reliability modelling of industrial and commercial demand side response

In the second part of Report D4 [12] on the reliability performance of smart distribution networks a study was made of the network-centric reliability performance to be expected from DSR.

5.4.1 DSR Capacity Credit: Comparison of alternative assessment methodologies

The present distribution network planning standard, Engineering Recommendation P2/6 (ER P2/6) [20], defines redundancy requirements of distribution network and hence drives network reinforcement and planning. In addition, ER P2/6 specifies a capacity contribution of distributed generation (DG) that can be used in network planning. Based on a range of successful demonstration and trials carried out Low Carbon London, UK Power Networks has developed a number of DSR schemes to substitute for network reinforcement, with the present ER P2/6 approach used to quantifying the contribution of DSR to network security.
Potential benefit of generation and demand led Demand Side Response (DSR) to distribution networks is in deferring upgrades driven by load growth. In this work, based on trials conducted in Low Carbon London, DSR contribution to security of supply is assessed using probabilistic risk modelling framework to further inform a number of topics:

- Reliability contribution of DSR technologies in a network context;
- Strengths and weaknesses of ER P2/6 in estimating contribution to security of supply;
- Benefits of contractual redundancy;
- Impact of DSR coincidence in delivery (common mode failures) on contribution to security; and
- Impact of DSR scale / magnitude on contribution to security of supply.

The P2/6 approach applies reliability modelling of individual non-network technologies without considering the actual distribution network. Hence, the present approach offers limited insight into the actual reliability implications associated with the use of DSR in particular scenarios. The reason is that the reliability delivered to end consumers is ultimately driven by the reliability characteristic of both, the actual network and DSR. This work considers the reliability worth based capacity credit that may be attributed to DSR in a network context.

One of the objectives of this work is to compare the levels of capacity contribution that correspond to the different definitions adopted for network adequacy studies:

- Effective Load Carrying Capability (ELCC) is the amount by which the load may be increased in the presence of DSR facilities while the original risk is maintained;
- Equivalent Firm Capacity (EFC) is the amount of capacity of ideal, never fails, source, which can replace DSR facilities while the supply risk is maintained; and
- Equivalent Network Capacity (ENC) is quantified by increase in network capacity based on equivalent circuit with the reliability performance of the real network, which can replace DSR facilities while the supply risk is maintained.

Each of the methods, including method used in ER P2/6, for determining capacity credit of DSR facilities are compared against network needed to ensure compliance to the security standard. The approach is illustrated in Figure 30.

**Figure 30: Illustration of the approach for comparison of different methods for capacity credit of DSR facilities (Source: LCL Report D4).**

A network (capacity X) and a DSR that supply Group Demand D+ ΔD are considered. Each of the capacity credit methodologies calculate different values of ΔD. The key task is to compare the reliability performance delivered by DSR (with different capacity credits derived by alternative methods) against required network reinforcement.

For illustration, two transformer circuits are considered with each circuit rating of 15 MVA. Different levels of reliability of theses circuits is considered assuming failure rate of 2%, 10% and 20% occurrences per year (which is equivalent to one failure on average, every 50, 10 or 5 years respectively) with a Mean Time To Repair (MTTR) of 24 and 240 hours (i.e. expected duration of outage of between 1 day and 10 days).
Table 8 shows the results of an example with three DSR facilities and with different reliability measures of circuit mean time to repair and circuit failure rate and different capacity credit methods. The group demand increase achieved with the DSR facility is shown, as calculated by each of the methods.

In each case, the group demand increase could have been equally achieved with a conventional replacement of both transformers with transformers with a rating equal to D+ΔD. Importantly the two columns under Expected Energy Not Served (EENS) quantify the energy at risk in the two cases, of using the DSR facility and using the conventional up-rating approach. The EENS is calculated as the sum of expectations of energy not supplied across all system states. The expectation of energy not supplied for one state is calculated by multiplying the area under the load duration curve and above the state capacity with state probability. This includes all potential combinations of intact system, N-1, N-2, and etc. The LDC is obtained by using an average LDC shape and scaling it to match the Group Demand. For visual analysis various figures are shown below.

Table 8: Results for an example with three DSR facilities

<table>
<thead>
<tr>
<th>Circuit MTTR (h)</th>
<th>Circuit failure rate (%)</th>
<th>Method</th>
<th>Contribution</th>
<th>(GD increase MW)</th>
<th>EENS (kWh)</th>
<th>Using DSR</th>
<th>Conventional up-rating</th>
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<tbody>
<tr>
<td>24</td>
<td>2%</td>
<td>P2/6</td>
<td>60.0%</td>
<td>1.80</td>
<td>5.40</td>
<td>0.36</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>ELCC</td>
<td>11.9%</td>
<td>0.36</td>
<td>0.32</td>
<td>0.33</td>
<td></td>
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<td></td>
<td></td>
<td>EFC</td>
<td>11.7%</td>
<td>0.35</td>
<td>0.32</td>
<td>0.33</td>
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<td></td>
<td></td>
<td>ENC</td>
<td>12.6%</td>
<td>0.38</td>
<td>0.33</td>
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<td></td>
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<tr>
<td></td>
<td>10%</td>
<td>P2/6</td>
<td>60.0%</td>
<td>1.80</td>
<td>33.10</td>
<td>8.89</td>
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<td></td>
<td></td>
<td>ELCC</td>
<td>20.9%</td>
<td>0.63</td>
<td>7.94</td>
<td>8.27</td>
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<td></td>
<td>EFC</td>
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<td>7.86</td>
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<td></td>
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<td></td>
<td>ENC</td>
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<td>8.31</td>
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<td></td>
<td>20%</td>
<td>P2/6</td>
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<td>81.43</td>
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<td></td>
<td>ELCC</td>
<td>26.2%</td>
<td>0.79</td>
<td>31.73</td>
<td>33.39</td>
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<td></td>
<td></td>
<td>EFC</td>
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<td></td>
<td>ENC</td>
<td>30.4%</td>
<td>0.91</td>
<td>33.66</td>
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<tr>
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<td>2%</td>
<td>P2/6</td>
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<td>1.80</td>
<td>81.43</td>
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<tr>
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<td>0.91</td>
<td>33.66</td>
<td>33.66</td>
<td></td>
</tr>
<tr>
<td></td>
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<td>P2/6</td>
<td>60.0%</td>
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<td>884.55</td>
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<td></td>
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<td>ELCC</td>
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<td>775.26</td>
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<tr>
<td></td>
<td></td>
<td>ENC</td>
<td>49.7%</td>
<td>1.49</td>
<td>868.26</td>
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</tr>
<tr>
<td></td>
<td>20%</td>
<td>P2/6</td>
<td>60.0%</td>
<td>1.80</td>
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</table>
As expected, in highly reliable networks (characterised with low circuit failure rates and short repair/restoration times) the ELCC, EFC and ENC methods allocate a much lower contribution to DSR if that same high reliability is to be maintained and hence would result in a lower increase of Group Demand when compared with P2/6. In practice however, this reliability may already be well in excess of P2/6 requirements due to the other incentives, which are in place in the GB regulatory environment, in particular the Interruption Incentive Scheme. The ENC and P2/6 methods produce similar contributions in networks with low reliability (failure rate 20% and MTTR of 240 hours).

It is important to note that the EENS associated with P2/6 approach to determining capacity contribution of DSR is significantly higher when compared with EFC, ENC and ELCC approaches, particularly in highly reliable networks. Furthermore, EENS when DSR is used to substitute for network reinforcement is very similar to the EENS in case of idealised conventional up-rating, when EFC, ENC and ELCC approaches are used. This is in stark contrast to P2/6 approach, as the EENS is very significant in cases when DSR is used to provide security of supply, in comparison to the EENS associated with conventional up-rating of the network. This difference diminishes in networks characterised with low reliability.

It is important to observe that in case of P2/6 approach, a significant part of the EENS is driven by the N-1 condition, while in the EFC, ENC and ELCC based methods the EENS is dominated by the N-2 condition.

Key observations are as follows:

- ELCC, EFC and ERC approaches consider network reliability, when quantifying DSR contribution to security of supply, the level of DSR contribution, measured by ELCC, EFC and ERC approaches, depends on the reliability of the network (not considered in ER P2/6);

- The level of DSR contribution, measured by ELCC, EFC and ERC approaches have relatively similar performance, especially for ELCC and EFC approaches;

- ELCC, EFC and ERC contribution reduces with increase in penetration level of DSR and with coincidence in delivery (common mode failure);

- In highly reliable networks the ELCC, EFC and ENC methods allocate much lower contribution to DSR and hence would result in lower increase of Group Demand when compared with P2/6. ENC method and ER P2/6 produce similar contributions in networks with low reliability (for example, failure rate of 20% and MTTR of 240 hours), and

- EENS is relatively stable for ELCC, EFC and ERC approaches when compared to P2/6 approach and EENS in ER P2/6 approach significantly depends on (a) the volume of DSR when compared size of Group Demand and (b) the existence of common mode failure - effects that ignored in P2/6. In this context, the reliability of network with DSR, when capacity credit is determined by ER P2/6, is significantly lower than compared with other methods for deriving DSR capacity value, particularly in highly reliable networks. For example, for case of circuits’ failure rate of 2% and MTTR of 24 hours and three DSR facilities the EENS is more than 15 times larger of ENC facilities. In networks with lower circuit reliability the difference diminishes.

The following recommendations are drawn:

- Network circuits parameters and reliability should be considered when estimating contribution of DSRs to security of supply (not the case with P2/6);

- Contractual redundancy improves the probability of delivering P2/6 contribution and should be considered;

- Consideration of diversity and common mode failures of DSR may be relevant; and

- When evaluating contribution to security of supply of DSR, relative volume of DSR in the context of the size of Group Demand should be considered.

Although this analysis identified a number of weaknesses of the present standard, ER P2/6 based-evaluation of the contribution of DSR as carried out in Learning Report 4 (which is then used to establish contracts with DSR following Low Carbon London Trials), is fully justified as ER P2/6 is the existing network standard and only available framework for quantifying capacity contribution of DSR. It is however important to mention that the fundamental review of the ER P2/6 will be carried out next year.

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7 Note that in case of ENC, driven by its very definition, the EENS when DSR is used to substitute for network reinforcement is exactly equal to the EENS in case of idealised conventional up-rating.
5.5 Improving current commercial and regulatory arrangements

In Report D5 [19], Novel commercial arrangements and the smart distribution network, we identify 12 areas for improvement that pertain to distribution system planning, operation, delivery as well as the overall regulation structure. Key observations can be summarised as follows:

- The current regulatory framework and existing revenue model for network operators may be hindering the business viability of advanced operational measures such as DSR. It is imperative that the value of such attractive cost-efficient solutions is recognised and their deployment is incentivised by rendering them viable business options.

- Multiple benefits potentially generated by technologies embedded at the distribution level such as DSR and generation are not fully utilised in the current system due to lack of integration with national-level markets. The increasing scope for synergies and conflicts may warrant the establishment of a Distribution System Operator to coordinate interactions with the upstream system in a compressive manner. Novel concepts such as Virtual Power Plants (VPPs) will be instrumental in providing the necessary cross-system control interface. These arising synergy opportunities must also be considered in the planning philosophy of distribution networks, where the applicability of whole systems design approaches is set to become increasingly important.

- The current planning standards do not recognise the option value of flexible assets and can be problematic in balancing the needs of present and future consumers. In view of the increasing uncertainty, it is imperative that network planning moves beyond the current deterministic paradigm in order to identify attractive openings for strategic investments. At the same time, the risks and complexity associated with large-scale deployment of novel technologies must be investigated; updated design standards will need to review the suitability of traditional practices and consider potential harmonics and fault level issues.

- Network investment is administered in a top-down approach without prior engagement with the actual system users, exacerbating the issue of planning uncertainty and potentially foregoing coordination opportunities. In addition, there is no framework to enable the emergence of market-solicited solutions in a bottom-up fashion and the aspect of actual project delivery suffers from lack of competition. Examples of alternative user-driven investment and competitive delivery arrangements from around the world are presented and discussed, highlighting potential improvements to the status quo.

5.6 dToU-based control of DSR for distribution network management

A distributed DSR control approach, based on dynamic Time-of-Use pricing, is investigated as an alternative of traditional centralised control architectures that face significant scalability and privacy challenges. This approach optimises the actions of DSR resources without requiring any centralised knowledge of their properties by the DNO. A suitable designed set of time- and location-specific power prices are transmitted to the DSR Energy Management Systems (EMS) and the latter independently determine their own control actions by minimising the users’ payments given their preferences and constraints.

However, naïve application of dToU-based control in combination with the envisaged automation in DSR control leads to serious loss of diversity and DSR concentration effects, as demand-led DSR attempts to consume as much as possible at the lowest-priced periods of the control horizon, this response concentration might breach the voltage and/or thermal limits of the distribution network (Figure 31 and Figure 32) and increase network losses.

"""Low Carbon London is not a ‘quick fix’. We have gained a clearer and more informed picture of all the challenges that the distribution network will face in the future. The project results inform our long-term low carbon strategy considering new skills and training required, which will be relevant to other cities facing the same challenges."""
In order to avoid such concentration effects and achieve more efficient network operation, three different smart measures are proposed, customised to the specific operating properties of different DSR types and tested in case studies on a LCL feeder. In the first one, a relative flexibility restriction signal is transmitted to the DSR EMS. In case of flexible loads with continuously adjustable power levels (e.g. electric vehicles-EV), this restriction corresponds to a maximum power limit, preventing each of these loads from requesting a large proportion of its total energy requirements at the lowest-priced periods. In case of flexible loads that cannot continuously adjust their power levels but can only defer their fixed operation cycles (e.g. wet appliances-WA), this restriction corresponds to a maximum cycle delay limit, preventing them from synchronizing their operation at the lowest-priced periods.

Figure 31. Power flow at feeder section 910-90069 under different EV dToU-based control approaches (Source: LCL Report D5).

Figure 32. Power flow at feeder section 910-90069 under different WA dToU-based (Source: LCL Report D5).
control approaches (Source: LCL Report D5).

However, imposing a flexibility restriction may not be deemed acceptable by the consumers as it may be considered as a direct intervention of the DNO in the control of their loads. In this context, an alternative proposed measure replaces the hard flexibility restriction by a soft non-linear price signal, penalizing the extent of flexibility utilised by the flexible loads. Specifically, this price penalizes the square of the power demand and the duration of cycle delay of continuously adjustable and deferrable cycle loads respectively. Regarding the former type, this non-linear pricing approach is demonstrated to outperform the flexibility restriction approach in flattening the demand profile and thus achieving more efficient solutions (Figure 31). Regarding the latter type, a third proposed smart measure randomising the non-linear price signal posted to different loads is demonstrated to bring significant additional benefits (Figure 32).

5.7 Virtual power plants and the distribution system operator

Virtual Power Plant (VPP) is the primary vehicle for facilitating closer and active interaction between TSO and DSO in order to access and control the DSR embedded deep at distribution level. A Virtual Power Plant is a flexible representation of a portfolio of DSR that can be used to make contracts in the wholesale market and to offer services to the system operator – subject to firmness of access to distribution networks. A VPP not only aggregates the capacity of many diverse DSR resources, it also creates a single operating profile from a composite of the parameters characterising each DSR resource and incorporates spatial (i.e. network) constraints into its description of the capabilities of the portfolio.

The VPP enables more active TSO/DSO interaction and facilitates a shift from isolated operation of energy supply, transmission and distribution businesses towards a more integrated (whole system) approach. DSO will have an active role in informing the TSO regarding the controllable VPP capability and will offer access to VPP operators to distribution networks. The TSO then can use the VPP as resources to manage the congestion in the national transmission system and for system balancing to improve the utilisation of low carbon technology assets and renewable energy. Through the VPP concept, the overall potential and economic value of DSR can be maximised considering both national and local objectives.

In the report, the concept of VPP and the role of DSO in supporting energy market operation and system management are described. It is envisaged that the system management responsibilities seen at TSO level will be devolved down to DSO level. The future highly distributed system will require more system management services at distribution level, and thus the interactions between the Commercial based VPP (CVPP) and DSO (with a Technical based VPP) strengthen.

The key results of the illustrative studies demonstrating the application of VPP concept on a Low Carbon London 11 kV system including the Engineering Instrumentation Zones (EIZs) in Brixton are presented in the report. The system set up for these studies also contain some DGs (CHP generators) and flexible Industrial and Commercial loads that have been the subject of the investigations in the Low Carbon London project. The studies were carried out by employing Imperial College London’s VPP tool, which assessed the operating characteristics of the VPP area at various system operating conditions.

It can be concluded that the active and reactive power capability of the VPP is affected by the changes in the operating conditions of the VPP area and the level of temporal local constraints. An example is given in Figure 33 where the PQ capability of the VPP decreases due to fault driven network re-configuration in the VPP area. The comparison between the VPP parameters in the intact system and the parameters after the network reconfiguration following the fault at SE_1 supply transformer is presented in Figure 33.

TVPP and CVPP are practical derivations of the VPP concept to aid interaction of DSR in the commercial energy markets as well as in the technical operation of the power system. TVPP incorporates the spatial constraints in the aggregation process. On the other hand, CVPP does not incorporate the spatial constraints. This allows commercial aggregation of DSR in different and remote locations in contrast to the TVPP. By default, unless otherwise specified, VPP corresponds to the TVPP.
After network reconfiguration, the capability of the VPP to increase its load reduced significantly from 12.64 MW in the intact system to 2.34 MW as the electrical distance (i.e. impedance) between the farthest load/generation bus and the supply bus increases. The reactive capability of the VPP also reduced, for example the maximum reactive power injection ($Q_{\text{max}}$) reduced from 7.33 MVAR to 2.30 MVAR. However, the capability of absorbing reactive power increased slightly from 1.04 MVAR to 2.18 MVAR. The impact on the reactive capability of the VPP also changed the scheduled reactive power load of the VPP from 6.29 MVAR to 1.31 MVAR while keeping almost the same MW load.

The studies also demonstrate that the use of VPP resources within the VPP operating capability calculated by the tool will not violate the local network constraints and therefore it prevents conflict between different VPP applications, for example for local network management and system balancing. The results of the studies also demonstrate that the use of resources within the VPP area is carried out in an efficient economic manner.

The VPP concept enables closer interaction between TSO and DSO and allows the integration of the whole system in managing the synergies and conflicts between distribution network, energy supply, transmission network, and the EU interconnection objectives when allocating DSR flexibility, which is key for optimal development of the GB system as a whole.

5.8 DSR contracts and baselining methods

Report D5 [19] discusses commercial arrangements pertaining to embedded resources and more specifically the operation of DSR. Beyond access to market, another issue that currently impedes DSR is the practical issue of measuring the actual demand response provided. To this end, we survey the existing literature and explore different baselining methods using data obtained from the Low Carbon London trials.
Table 9 summarises the strengths and weaknesses of the main categories of baseline. Linear regression and ARIMA are not usually used in fulfilling DSR contracts because of their relative complexity. However, they offer improved accuracy (especially if large amounts of historical data are available) and very low bias, even when no adjustment is made [24]. It may be that in the future an app on a tablet or laptop can be used to implement baselines, hiding the complexity behind a simplified input interface that also explains the working of the baseline in simple terms. Having said this, the comparisons in [22], [23] and [24] show that the gains to be made, especially over a symmetric high X of Y baseline, are small and that the intrinsic variability in load of a site may dominate over any gains to be made by choice of baselining method.

Another consideration is that, in the distribution network context, it is much more important that demand reduction (in kW) is maintained throughout the duration of the event, as only a small number of high capacity DSR sites may be used to support an overloaded asset and minimising the duration of exposure of any asset to overload is crucial. For this reason it is likely that contracts currently in use for STOR based DSR would need to be adapted to include penalties for low compliance. Asymmetric high X of Y baselines are currently favoured for DSR payment calculations because they are simple to implement and understand and do not penalise participants if they reduce demand in advance of a DSR call. However, Coughlin et al [22] and Wijaya et al [24] show that they suffer significant bias and inaccuracy. In the distribution network context this may not be acceptable because it is much more important to have as accurate as possible predictions of demand reduction when just a few high capacity sites are supporting a single overloaded asset.

Symmetric high X of Y baselines, however, although not quite as accurate or lacking in bias as regression or ARIMA (provided sufficient historical data are available), provide an excellent balance between simplicity, accuracy and robustness. As for all X of Y baselines, symmetric high X of Y baselines have the advantage of filtering out days with unusual demand patterns. The disadvantage that they may be a little less favourable to participants should be weighed against these benefits.

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<table>
<thead>
<tr>
<th>Baselining method</th>
<th>Strengths</th>
<th>Weaknesses</th>
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<tbody>
<tr>
<td>Linear regression</td>
<td>Accurate and robust, low bias</td>
<td>Requires whole season of data for best accuracy. More complex than high X of Y</td>
</tr>
<tr>
<td>ARIMA</td>
<td>Very accurate and robust, low bias</td>
<td>Quite complex and requires a large amount of data to achieve best accuracy</td>
</tr>
<tr>
<td>High X of Y (Symmetric)</td>
<td>Good balance of simplicity, accuracy and robustness, low bias</td>
<td>May disadvantage those turning down in anticipation of an event</td>
</tr>
<tr>
<td>High X of Y (Asymmetric)</td>
<td>Good balance of simplicity, accuracy and robustness, favourable to DSR participants</td>
<td>Less accurate than symmetric causing overpayment by aggregator/DNO, high bias</td>
</tr>
</tbody>
</table>

Table 9. Comparison of baselining methods

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9 They are typically used for analysis: to help a site manager understand building load and how it may be reduced, for example.

10 ‘Compliance’ is the percentage of the event time for which the demand reduction is maintained above the contracted amount - see LCL Report A7 [13]
Distributed generation and demand side response

Contracting with industrial & commercial customers to support the network at peak demand times

Installing 5500 smart meters to monitor residential demand for electricity

Unique dynamic time of use tariff to test the elasticity of demand for electricity from 1100 residential customers

Low Carbon London

Low Carbon London has used London as a test bed to develop a smarter electricity network that can manage the demands of a low carbon economy and deliver reliable, sustainable electricity to businesses, residents and communities

We welcome your feedback: innovation@ukpowernetworks.co.uk
Electrification of heat and transport

Analysis of the effect of heat pumps and electric vehicle charging.

Testing the impact and feasibility of automatic control by network operators.

Network planning and operation

Low Carbon London has provided insight into how we will be able to better design, plan and operate our networks in a low carbon future.
References


References

Conclusion of “Using Smart Meters and Substation Sensors to Facilitate Smart Grids” trials:

- Understanding customer behaviour and potential network impact (Appendix 2, Use Case U04.1)
- Use of smart meter information to support distribution network planning and design (Appendix 2, Use Case U04.2)
- Use of smart meter data to support network operations

Complete Q3, 2014

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<tr>
<th>Successful Delivery Reward criterion</th>
<th>Evidence</th>
<th>LCL Project output</th>
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<td>Conclusion of “Using Smart Meters and Substation Sensors to Facilitate Smart Grids” trials:</td>
<td>1-1 Accessibility and validity of smart meter data</td>
<td>LCL Report C5 - Accessibility and validity of smart meter data</td>
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<td>2-1 Network state estimation and optimal sensor placement</td>
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<td>LCL Report C1 - Use of smart meter information for network planning and operation</td>
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<td>Successful Delivery</td>
<td>Evidence</td>
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<td><strong>Conclusion of “Enabling and Integrating Distributed Generation” trials:</strong></td>
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<td>DNO learning report for facilitating DG connections</td>
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<p>| <strong>Conclusion of “Enabling Electrification of Heat and Transport” trials:</strong> | | |
| Exploring impact of electric vehicle charging (Appendix 2, Use Case U03.1) | 3-1 Impact of LV connected DER on power quality | LCL Report B3 - Impact of Low Voltage – connected low carbon technologies on Power Quality |
| Exploring the impact of heat pump demand (Appendix 2, Use Case U03.2) | 5-1 Impact of opportunities for wide-scale electric vehicle deployment | LCL Report B1 - Impact and opportunities for wide-scale Electric Vehicle deployment |
| | 4-2 Impact of LV DERs on network utilisation | LCL Report B4 - Impact of Low Voltage – connected low carbon technologies on network utilisation |
| | DNO learning report on opportunities for smart optimisation of new heat &amp; transport loads | LCL Report B5 - Opportunities for smart optimisation of new heat and transport loads |
| Complete Q3, 2014 | | |</p>
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<td>LCL Report A10 Smart appliances for residential demand response</td>
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<td>DNO guide to residential DR for outage management and as an alternative to network reinforcement</td>
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<td>Conflicts and synergies of DR</td>
<td>LCL Report A5 - Conflicts and synergies of Demand Side Response</td>
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<td>DNO impacts of supply-following DR report</td>
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## Successful Delivery

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<td>14-2 Carbon impact of smart distribution networks</td>
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<td>14-3 Overall summary report</td>
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<td>DNO design and operations learning report</td>
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<td>DNO tools and systems learning report</td>
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## Glossary

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<th>Term</th>
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<th>ICL</th>
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<td>ADQM</td>
<td>Address Data Quality Management</td>
<td>IE</td>
<td>Instant Energy</td>
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<td>AF</td>
<td>(PI) Asset Framework module</td>
<td>IEC</td>
<td>International Electrotechnical Commission</td>
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<td>ALCS</td>
<td>Ancillary Load Control Switch</td>
<td>IET</td>
<td>Institution of Engineering and Technology</td>
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<td>AMI</td>
<td>Advanced Metering Infrastructure</td>
<td>IHD</td>
<td>In-Home Display</td>
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<td>ANM</td>
<td>Active Network Management</td>
<td>IOA</td>
<td>Institute of Applied Optimisation</td>
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<tr>
<td>BAU</td>
<td>Business As Usual</td>
<td>IPSA</td>
<td>A proprietary network planning tool</td>
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<tr>
<td>CB</td>
<td>Circuit Breaker</td>
<td>IT</td>
<td>Information Technology</td>
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<td>CBA</td>
<td>Cost-Benefit Analysis</td>
<td>IVR</td>
<td>Interactive Voice Response</td>
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<td>CEP</td>
<td>Complex Event Processing</td>
<td>LCL</td>
<td>Low Carbon London</td>
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<td>CHP</td>
<td>Combined Heat and Power</td>
<td>LCNF</td>
<td>Low Carbon Network Fund</td>
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<td>(IEC 61970/61968/62325) Common Information Model</td>
<td>LCT</td>
<td>Low-Carbon Technology</td>
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<td>CLI</td>
<td>Caller Line Identification</td>
<td>LFMM</td>
<td>Load Forecast Macro Model</td>
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<td>CI</td>
<td>Customer Interruptions</td>
<td>LIC</td>
<td>(ANM) Local Interface Controller</td>
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<td>CML</td>
<td>Customer Minutes Lost</td>
<td>LV</td>
<td>Low Voltage – any voltage below 1kV</td>
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<td>CNO</td>
<td>(Electric Vehicle) Charging Network Operator</td>
<td>MD</td>
<td>Maximum Demand (register on a meter)</td>
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<td>CO2</td>
<td>Carbon Dioxide</td>
<td>MDI</td>
<td>Maximum Demand Indicator</td>
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<td>CP</td>
<td>Charging Post</td>
<td>MDM</td>
<td>Meter Data Management</td>
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<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>CRM</td>
<td>Customer Relationship Management</td>
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<tr>
<td>CS</td>
<td>Carbon Sync (Pod Point charging post controller)</td>
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<tr>
<td>CSV</td>
<td>Comma-Separated Value (file format)</td>
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<td>CT</td>
<td>Current Transformer</td>
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<td>DCC</td>
<td>The national Data Collection Company for smart meter data</td>
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<td>DG</td>
<td>Distributed Generation</td>
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<td>DMS</td>
<td>Distribution Management System</td>
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<td>Distribution Network Operator</td>
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<td>Distributed Network Protocol v3.0 – a standard SCADA communications protocol</td>
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<tr>
<td>DPIan</td>
<td>A proprietary network planning tool</td>
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<tr>
<td>DQM</td>
<td>Data Quality Management</td>
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<tr>
<td>DSR</td>
<td>Demand-Side Response</td>
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<tr>
<td>dToU</td>
<td>Dynamic Time-of-Use (tariff)</td>
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<tr>
<td>DUsS</td>
<td>Distribution Use of System – the basis on which DNOs charge for the use of their networks</td>
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<td>EAC</td>
<td>Estimated Annual Consumption</td>
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<td>EAM</td>
<td>Enterprise Asset Management (system)</td>
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<tr>
<td>EIZ</td>
<td>(LCL) Engineering Instrumentation Zone</td>
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<tr>
<td>ENA</td>
<td>Energy Networks Association</td>
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<td>ESB</td>
<td>Enterprise Service Bus</td>
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<tr>
<td>ETL</td>
<td>Extract/Transform/Load (application interfacing pattern)</td>
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<tr>
<td>ETR</td>
<td>Engineering Technical Recommendation</td>
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<td>EV</td>
<td>Electric Vehicle</td>
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<tr>
<td>EHV</td>
<td>Extra High Voltage – 22kV or above</td>
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<td>FALCON</td>
<td>Flexible Approaches to Low Carbon Optimised Networks (LCNF project)</td>
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<tr>
<td>FTP</td>
<td>File Transfer Protocol</td>
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<td>MPAN</td>
<td>Meter Point Administration Number</td>
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<td>MPRS</td>
<td>Meter Point Registration System</td>
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<tr>
<td>MPRS</td>
<td>Meter Point Registration System</td>
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<tr>
<td>MW</td>
<td>MegaWatts – units of a million Watts</td>
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<tr>
<td>NDAG</td>
<td>Network DCC Access Gateway</td>
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<tr>
<td>NHH</td>
<td>Non-Half-Hourly (consumption settlement method)</td>
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<tr>
<td>NHHDA</td>
<td>Non-Half-Hourly Data Aggregator</td>
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<td>NOP</td>
<td>Normally Open Point</td>
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<tr>
<td>OFGEM</td>
<td>The Office of Gas and Electricity Markets</td>
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<tr>
<td>ODS</td>
<td>Operational Data Store</td>
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<tr>
<td>OMS</td>
<td>Outage Management System</td>
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<tr>
<td>OT</td>
<td>Operational Technology, eg real-time systems, RTUs, SCADA equipment etc</td>
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<tr>
<td>P</td>
<td>Active Power</td>
<td></td>
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<tr>
<td>PAF</td>
<td>Postal Address File</td>
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<tr>
<td>PC</td>
<td>(a) Personal Computer (b) Profile Class</td>
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<tr>
<td>PI</td>
<td>Proprietary OSIsoft SCADA historian</td>
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<tr>
<td>PMS</td>
<td>Participant Management System</td>
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<tr>
<td>PV</td>
<td>Photo-Voltaic (embedded generation)</td>
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<tr>
<td>Q</td>
<td>Reactive Power</td>
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<td>RIIO</td>
<td>Revenue = Incentives + Innovation + Outputs – a new performance-based model for setting energy network companies’ price controls</td>
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<td>RIIO-ED1</td>
<td>The regulatory DNO price control period from 1/4/2015 to 31/3/2023</td>
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<td>RMS</td>
<td>Root Mean Square</td>
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<td>RTU</td>
<td>Remote Terminal Unit</td>
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<tr>
<td>S</td>
<td>Apparent Power</td>
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<tr>
<td>SM</td>
<td>Smart Meter</td>
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<tr>
<td>SME</td>
<td>Small-and Medium-size Enterprise</td>
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<tr>
<td>Term</td>
<td>Description</td>
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<tr>
<td>FUN-LV</td>
<td>Flexible Urban Networks – Low Voltage (LCNF Tier 2 project)</td>
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<tr>
<td>GS9</td>
<td>Larger embedded generation facilities, capable of delivering more than 16A per phase at LV</td>
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<tr>
<td>G83</td>
<td>Small-scale embedded generation, below 16A per phase at LV</td>
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<tr>
<td>GIS</td>
<td>Geographical Information System</td>
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<td>GLA</td>
<td>Greater London Authority</td>
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<td>GPRS</td>
<td>General Packet Radio Service</td>
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<tr>
<td>GROND</td>
<td>A proprietary network planning tool</td>
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<tr>
<td>HA</td>
<td>Harmonic Analysis</td>
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<tr>
<td>HH</td>
<td>Half-Hourly (readings/measurements or consumption settlement method)</td>
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<tr>
<td>HMI</td>
<td>Human-Machine Interface</td>
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<tr>
<td>HP</td>
<td>Heat Pump</td>
<td></td>
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<tr>
<td>HV</td>
<td>High Voltage –1kV or above but below 22kV</td>
<td></td>
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<tr>
<td>I</td>
<td>Current</td>
<td></td>
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<tr>
<td>I&amp;C</td>
<td>Industrial and Commercial</td>
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<td>ICCP</td>
<td>Inter Control Centre Protocol – IEC 60870-6/TASE.2</td>
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<tr>
<td>SMETS2</td>
<td>The national Smart Metering Equipment Technical Specification</td>
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<td>SMIP</td>
<td>The national Smart Meter Implementation Programme</td>
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<tr>
<td>SMTP</td>
<td>Simple Mail Transfer Protocol</td>
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<td>SSC</td>
<td>Standard Settlement Configuration</td>
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<td>Smart Urban Low Voltage Networks</td>
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<td>(IEC) Technical Committee 57</td>
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<td>ToU</td>
<td>Time-of-Use (tariff)</td>
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<tr>
<td>TSO</td>
<td>Transmission System Operator</td>
<td></td>
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<tr>
<td>UKPN</td>
<td>United Kingdom Power Networks</td>
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<tr>
<td>UPS</td>
<td>Uninterruptible Power Supply</td>
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<td>VBA</td>
<td>Visual Basic for Applications</td>
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<tr>
<td>VIPQ</td>
<td>Voltage, current, active and reactive power (measurements)</td>
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<tr>
<td>VPN</td>
<td>Virtual Private Network</td>
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<tr>
<td>WAN</td>
<td>Wide-Area Network</td>
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<tr>
<td>XML</td>
<td>Extensible Markup Language</td>
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<tr>
<td>Instrumenting a Smart Grid</td>
<td>Electrification of heat</td>
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<tr>
<td>ANM/network operation</td>
<td>Electrification of transport</td>
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<tr>
<td>Dynamic Time of Use tariff</td>
<td>Energy efficiency</td>
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<tr>
<td>Demand Side Response – demand</td>
<td>Demand Side Response – generation</td>
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<tr>
<td>Smart meter</td>
<td>Network planning</td>
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<tr>
<td>Distributed Generation</td>
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</table>
Project Overview

Low Carbon London, UK Power Networks’ pioneering learning programme funded by Ofgem’s Low Carbon Networks Fund, has used London as a test bed to develop a smarter electricity network that can manage the demands of a low carbon economy and deliver reliable, sustainable electricity to businesses, residents and communities.

The trials undertaken as part of LCL comprise a set of separate but inter-related activities, approaches and experiments. They have explored how best to deliver and manage a sustainable, cost-effective electricity network as we move towards a low carbon future. The project established a learning laboratory, based at Imperial College London, to analyse the data from the trials which has informed a comprehensive portfolio of learning reports that integrate LCL’s findings.

The structure of these learning reports is shown below:

<table>
<thead>
<tr>
<th>Summary</th>
<th>SR: DNO Guide to Future Smart Management of Distribution Networks</th>
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<tbody>
<tr>
<td>Distributed Generation and Demand Side Response</td>
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<tr>
<td>A1 Residential Demand Side Response for outage management and as an alternative to network reinforcement</td>
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<td>A2 Residential consumer attitudes to time varying pricing</td>
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<tr>
<td>A3 Residential consumer responsiveness to time varying pricing</td>
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<tr>
<td>A4 Industrial and Commercial Demand Side Response for outage management and as an alternative to network reinforcement</td>
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<tr>
<td>A5 Conflicts and synergies of Demand Side Response</td>
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<tr>
<td>A6 Network impacts of supply-following Demand Side Response report</td>
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</tr>
<tr>
<td>A7 Distributed Generation and Demand Side Response services for smart Distribution Networks</td>
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<tr>
<td>A8 Distributed Generation addressing security of supply and network reinforcement requirements</td>
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</tr>
<tr>
<td>A9 Facilitating Distributed Generation connections</td>
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<tr>
<td>A10 Smart appliances for residential demand response</td>
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<tr>
<td>Electrification of Heat and Transport</td>
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<tr>
<td>B1 Impact and opportunities for wide-scale Electric Vehicle deployment</td>
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<tr>
<td>B2 Impact of Electric Vehicles and Heat Pump loads on network demand profiles</td>
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<tr>
<td>B3 Impact of Low Voltage – connected low carbon technologies on Power Quality</td>
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</tr>
<tr>
<td>B4 Impact of Low Voltage – connected low carbon technologies on network utilisation</td>
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<tr>
<td>B5 Opportunities for smart optimisation of new heat and transport loads</td>
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<tr>
<td>Network Planning and Operation</td>
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<tr>
<td>C1 Use of smart meter information for network planning and operation</td>
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<tr>
<td>C2 Impact of energy efficient appliances on network utilisation</td>
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</tr>
<tr>
<td>C3 Network impacts of energy efficiency at scale</td>
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<tr>
<td>C4 Network state estimation and optimal sensor placement</td>
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<tr>
<td>C5 Accessibility and validity of smart meter data</td>
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<tr>
<td>Future Distribution System Operator</td>
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<tr>
<td>D1 Development of new network design and operation practices</td>
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<tr>
<td>D2 DNO Tools and Systems Learning</td>
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<tr>
<td>D3 Design and real-time control of smart distribution networks</td>
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<tr>
<td>D4 Resilience performance of smart distribution networks</td>
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<td>D5 Novel commercial arrangements for smart distribution networks</td>
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<tr>
<td>D6 Carbon impact of smart distribution networks</td>
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