Carbon impact of smart distribution networks

Low Carbon London Learning Lab
Executive Summary
This report analyses and quantifies the implications of low-carbon technologies (LCTs) and solutions studied in the Low Carbon London (LCL) trials for the carbon emissions and renewable integration cost of the broader GB 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) Demand-Side Response (DSR), dynamic time-of-use (dToU) tariffs and energy-efficient and smart domestic appliances, are translated into nationally representative demand profiles. The impact of these findings on the CO₂ performance and wind integration cost of the electricity system is quantified using an advanced analytical model across three proposed scenarios covering 2030-2050 for the Great Britain system.

Given that the uncertainty of intermittent renewable output (primarily wind and solar PV) 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. This model is able to dynamically allocate all forms of balancing service (frequency response and reserve services), including optimal allocation between 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 was used to further investigate the impact of the provision of ancillary services from alternative sources on the carbon performance and renewable integration cost of the system. This is particularly relevant as the GB system is facing significant degradation in system inertia.

The results of the analysis suggest that LCTs are able to deliver measurable 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 to times of lower carbon grid intensity 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. Irrespective of the carbon scenario, or exactly which sources of DSR are adopted, there seems to be potential to reduce average system carbon emissions by an additional 5 g/kWh.

Carbon benefits of LCTs are generally more pronounced in scenarios with higher intermittent Renewable Energy Sources (RES) penetration, although there are limits to this trend where 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 would be significantly less carbon intensive if smart operation strategies are adopted, making a very positive impact on the overall carbon performance of the economy. Although the primary effort of climate change policy will remain on decarbonising the generation fleet and electrifying heat and transport sectors, the flexibility of LCTs can also provide a measurable incremental carbon benefit.

The second set of studies focused on the potential of DSR technologies to support cost-efficient integration of intermittent renewables. System integration benefits of DSR are assessed in the sense of reducing the overall system cost of intermittent RES. Figure 1 shows that the total Whole-System Cost (WSC) of intermittent RES is the sum of their Levelised Cost of Electricity (LCOE) and the system integration cost, where the latter is defined as the total of additional infrastructure and/or operating
costs to the system as a result of integrating renewable power generation. LCOE considers the capital cost and O&M cost of RES technologies over their project life while the system integration cost of RES includes the system capacity costs associated with capacity needed for security, balancing costs and the impact of RES output patterns.¹

![Whole-system cost of intermittent RES](image)

In this report we focus on the capability of smart LCTs to reduce the system integration cost of wind and solar PV generation by reducing:

- System balancing cost
- Cost of required back-up generation capacity
- Cost of replacing curtailed renewable 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 the future electricity system by reducing the renewable integration cost. Penetration of individual DSR technologies i.e. the uptake of e.g. EVs, HPs etc. is a critical factor affecting the value of DSR for wind integration, as it determines the volume of flexible system services that can be provided by DSR technologies.

Average RES integration benefits, when all smart LCTs coexist in the system, vary between £6.40 and £11.40/MWh of absorbed RES output across the three scenarios. The Marginal RES 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 RES capacity beyond the already high shares foreseen in future scenarios.

In addition to the projections of carbon benefits of LCTs that are covered in this report, Annex A presents the carbon footprint of the actual LCL trials. The net carbon effect of each trial area is calculated by assessing their impact against the Elexon grid mix carbon intensity. These trial assessments underpin the basis for the carbon effect in future scenarios discussed within the main body of this report. Further to Annex A, and using the data contained within this report, the LCL Summary Report (SR) provides a comparative assessment of the carbon and investment business cases at both bid stage and with the benefit of the project findings.

¹ Other components of system integration cost, not considered in this report, may include transmission and distribution network costs, as well as the cost of network losses; these components would reflect any requirements to reinforce transmission and distribution networks in order to accommodate wind and PV generation.
Table of Contents

Executive Summary .................................................................................................................................................. 2

1 Introduction .......................................................................................................................................................... 6

2 Overview of Low Carbon London solutions with potential for carbon reduction ............................................ 8
   2.1 Low Carbon London trials .............................................................................................................................. 8
      2.1.1 Electric vehicles ..................................................................................................................................... 8
      2.1.2 Heat pumps .............................................................................................................................................. 9
      2.1.3 Dynamic ToU tariffs ............................................................................................................................. 10
      2.1.4 Industrial and commercial demand-led DSR ...................................................................................... 10
   2.2 Carbon assessment of Low Carbon London trials ....................................................................................... 11

3 Scenarios and modelling approach ................................................................................................................ 12
   3.1 Imperial’s Advanced Stochastic Unit Commitment (ASUC) model .............................................................. 12
      3.1.1 Methodology ......................................................................................................................................... 12
      3.1.2 Advantages of stochastic scheduling approach in systems with high penetration of intermittent renewables .................................................................................................................................................. 13
   3.2 Scenarios for carbon impact assessment of future GB electricity system ...................................................... 14
      3.2.1 Key sources of information ................................................................................................................... 14
      3.2.2 Scenarios for expected evolution of electricity generation and demand ............................................ 14
      3.2.3 Uptake scenarios for smart low-carbon technologies ........................................................................ 15

4 Quantitative assessment of carbon impact of smart distribution networks .................................................... 16
   4.1 Approach to quantifying the carbon impact of smart LCTs ........................................................................ 16
   4.2 Carbon benefits of smart management of LCTs ............................................................................................ 17
      4.2.1 Average system emissions ................................................................................................................... 17
      4.2.2 Carbon intensity of supplying electrified transport and heat demand ............................................ 19
      4.2.3 Avoided emissions per unit of smart demand ................................................................................... 21
   4.3 Summary of findings ..................................................................................................................................... 22

5 Impact of smart LCTs on renewable integration cost ........................................................................................ 24
   5.1 Challenges of RES integration ...................................................................................................................... 24
   5.2 Case studies .................................................................................................................................................. 25
   5.3 Average and marginal value of smart technologies ..................................................................................... 28
   5.4 Key findings on renewable integration benefits of smart technologies .................................................... 30

6 Findings and conclusions ................................................................................................................................... 31

References ............................................................................................................................................................... 32

Annex A: Carbon Tool output examples and carbon impact assessment of the LCL trials ................................... 34
A.1 General Overview.................................................................................................................. 35
A.2 Dynamic Time of Use Tariff .................................................................................................. 36
A.3 Distributed Generation ......................................................................................................... 43
A.4 Heat Pumps .......................................................................................................................... 45
A.5 Electric Vehicles .................................................................................................................. 49
A.6 Smart Metering .................................................................................................................... 52
A.7 Industrial and Commercial Demand Side Response.......................................................... 55
1 Introduction

Rapid expansion of Renewable Energy Sources (RES) and in particular wind and PV power in Great Britain (GB) is expected to make a key contribution to electricity system decarbonisation. However, high penetration of intermittent RES generation connected to the system will increase the requirements for various reserve and frequency regulation services. If these services are to be met by part-loaded or fast-start plants, this will not only reduce the system operational efficiency but will also limit the ability of the system to accommodate RES, leading to reduced carbon benefits and increased balancing cost. Moreover, large amount of additional generation capacity is required to provide “RES firming” for system security reasons, which gives rise to additional costs associated with wind integration. These system integration impacts increase the overall system cost of intermittent RES.

The challenges introduced by intermittent wind generation present significant opportunities for the flexibility service providers such as Demand-Side Response (DSR). In time, it is possible that new sources of Demand Response connected to the distribution network (i.e. residential customers, controlled charging of electric vehicles, and controlled heating load) could play a significant role, given that their flexibility can potentially reduce the negative economic and environmental impact of intermittency of wind and PV generation. In this context, this report analyses and quantifies the implications of low-carbon technologies (LCTs) and solutions studied in the Low Carbon London (LCL) trials for the carbon emission and wind integration cost within the broader UK electricity system. Therefore, the key specific objectives of this study can be summarized as follows:

- Analyse the benefits of LCTs trialled in LCL in reducing carbon emissions and wind integration cost in the broader UK electricity system for a range of long-term development scenarios. In particular, the LCTs investigated include: electric vehicles (EVs), heat pumps (HPs), industrial and commercial (I&C) DSR and dynamic time-of-use (dToU) tariffs for residential customers.
- Evaluate the carbon benefits of smart operation of LCTs in the context of electricity system decarbonisation and increased share of intermittent RES.
- Quantify the economic benefits of carbon savings from smart DSR operation in terms of lower requirements to invest in zero-carbon generation capacity in order to achieve the same carbon emission target.
- Analyse the benefits of smart operation of LCTs in reducing system integration cost of wind, including balancing cost associated with wind intermittency and investment cost associated with back-up capacity to ensure system security.

The key link between the technology-specific, bottom-up LCL trials and system-level studies presented in this report is the effective shape of electricity demand seen by large-scale generation for different deployment levels of trialled low-carbon solutions, but also the potential of these solutions to provide ancillary services to the system, in particular frequency response and reserve. Compared to previous published work, the uncontrolled charging or heating patterns are now based on measured populations, and the ability to shift has been updated based on insights from LCL. The possibility to source these services from the demand side rather than from centralised generation can significantly reduce the cost of operating the future power system and the resulting environmental burden.
The impact of various low-carbon solutions and technologies is investigated for several future system development scenarios, with particular emphasis on different possible evolution trajectories of wind and other intermittent renewable generation capacity. Given that the uncertainty and limited inertia capability of intermittent renewable output are expected to be a major driver for escalating integration cost and system emission, the performance of the system is analysed using Imperial’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, we further investigate the impact of the provision of frequency regulation from alternative sources on the carbon performance and wind integration cost of the system.

This report should be read in context alongside companion Low Carbon London report [13]. This report demonstrates the carbon benefits of widening the pool of Demand Response provision, but report [13] shows that, under existing market mechanisms there may be substantial competition for these resources amongst DNOs, TSO and suppliers, particularly commencing a decade from now.
2 Overview of Low Carbon London solutions with potential for carbon reduction

In this section we provide an overview of technologies investigated in LCL trials and specify their key characteristics with respect to the carbon reduction potential.

2.1 Low Carbon London trials

A number of technologies and solutions have been trialled within the LCL project that are expected to make a visible impact on the carbon emissions from the broader energy system. In this report we focus in particular on the following four LCTs:

- Electric Vehicles (EVs)
- Heat Pumps (HPs)
- Dynamic Time-of-Use (dToU) tariffs
- Industrial and Commercial Demand-Side Response (I&C DSR)

2.1.1 Electric vehicles

A detailed description of EV trials conducted in LCL is given in Report B1 [1]. The trial included residential and commercial vehicles and monitored their charging at both their home or office charging points, as well as at a number of public charging stations. The report quantified some of the key parameters of EV demand relevant for network planning and system analysis such as typical demand profiles and diversified peak demand for a given number of EVs.

As an illustration, the fully diversified average and peak day demand profiles for residential EV users are shown in Figure 2. The average profile represents the charging demand for an average day, while the peak profile has been obtained by extrapolating the diversity characteristic of EV peak demand towards a very large number of vehicles, where the coincidence factor approaches 20%. Given that the typical (non-diversified) charging power for a single residential charging point is around 3.5 kW, this results in a diversified peak EV demand of 0.7 kW. This information has been used to construct annual hourly demand profiles that were used as an input into the ASUC model used for this study.

---

2 Charging behaviour in the LCL EV trial was monitored for 72 residential and 54 commercial participants, while the data for public charging stations covered around 500 sites for a period of about 1 year.

3 Peak demand in this context corresponds to the worst-case maximum demand discussed in Section 3.1.3 of Report B1 [1].
LCL Report B1 has further assessed the flexibility of EV demand, i.e. how much of EV charging demand may be shifted in time in order to support the electricity system but without compromising the ability of the EV users to make their intended journeys. The analysis of smart charging in Report B1 suggested that between 70% and 100% of EV demand can be shifted away from peak hours. Based on the results of that analysis, we estimate that up to 80% of EV demand could be shifted away to other times of day while supporting the same journey patterns.\(^4\) This flexibility parameter is used as input into the ASUC model in order to allow it to make optimal scheduling decisions on when flexible EVs should be charged from the system operation perspective.

### 2.1.2 Heat pumps

LCL trials also involved the monitoring of residential heat pumps, as described in Report B4 [2]. Given that the trials only involved two dwellings, a 2-bedroom and a 4-bedroom home, the trial results were used to calibrate the likely non-diversified peak of residential heat pump load, however in order to construct a fully diversified profile of national-level HP demand, we used inputs from previous studies such as the ENA report [3], Micro-CHP Accelerator trial [4] or recent studies carried out for Carbon Trust [4], Department of Energy and Climate Change [6] and Climate Change Committee [7]. All of these assumed a gradual improvement in building insulation levels, and estimated the hourly profiles based on representative temperature fluctuations for the UK. The diversified peak day demand is shown in Figure 3 for illustration.

---

\(^4\) It has to be noted that this level of flexibility has been assumed as feasible given the charging and journey patterns of residential users, but it does not necessarily reflect the customers’ willingness to participate in smart charging schemes. Report B5 assumes that 30% of EV demand can be shifted based on residential dToU trials, but without specific consideration towards journey patterns. Given the focus of this report on 2030-2050 time horizon, more ambitious assumptions have been made in line with the flexibility implied by the users’ driving patterns. However, in the analysis of benefits of smart EV charging for reducing distribution network reinforcement (carried out in the companion LCL Report 11-1), given the focus on extreme peak conditions, we take a more conservative assumption of 50% of EV demand shifting.
We further assumed that flexible HP operation would be possible if they were fitted together with heat storage. Based on the findings of [3] and [8], we assumed that for the heat storage size in the order of 10% of peak day heating energy demand, the peak HP demand can be reduced by 35% through using the storage and shifting HP demand into other times of day\textsuperscript{5}.

2.1.3 Dynamic ToU tariffs
The impact of dToU\textsuperscript{6} tariffs on residential customer load has been investigated in detail in the LCL project using a relatively large sample, and the results of the analysis are provided in LCL Report A3 [9]. The analysis has found that the peak reduction of about 9% was achieved through time-differentiated tariffs, while the most engaged trial participants showed a peak reduction of 20%.

Based on these trial findings, we therefore assume in this study that if in future, consumers are educated to the point that today’s high-performers become the ‘new normal’, up to 20% of participating residential electricity demand may be flexible in order to support the efficient operation of the system and integration of intermittent renewables.

2.1.4 Industrial and commercial demand-led DSR
The potential of generation and demand-led I&C DSR resources to deliver services to the system has been investigated in the LCL trials, and the results have been analysed in detail in LCL Report A7 [10]. In this study we focus on the contribution of demand-led I&C DSR, which according to the trial was able to deliver significant reductions of commercial building load for a given periods of time. A number of participating sites were even prepared to fully switch off their air conditioning load for a limited period of time in order to deliver DSR services. DSR events were further found to be associated with significant demand for payback power and to a smaller extent payback energy, which potentially reduces the contribution of DSR sites to reducing network peaks, as illustrated in companion Report 11-1 [11].

For all of these reasons we take a conservative assumption that the achievable demand reduction for participating I&C customers is 10%.

\textsuperscript{5} In study “Understanding the Balancing Challenge” (DECC 2012) this assumption resulted in a hot water tank of about 140 litres per average household.

\textsuperscript{6} Dynamic ToU tariff refers to a dynamic time of pricing mechanism where high, normal and low price periods vary dynamically.
2.2 Carbon assessment of Low Carbon London trials

In addition to the projections made in this report, the carbon footprint of the Low Carbon London trials is illustrated in a separate and supporting annex to this report. The net carbon effect of each trial area (and in some cases, individual events) was calculated by assessing their impact against Elexon grid mix carbon intensity. Baseline CO₂ emissions were calculated prior to each event, and the impact of the trial, positive or negative calculated against this. These reports detail the carbon effect of the Low Carbon Trial and underpin the basis for the future scenarios discussed within this report.

The LCL trial carbon assessment therefore evaluates the present potential of LCL solutions to contribute to overall carbon reduction from the energy system. The figures from the carbon assessment reported and analysed in the annex provide a valuable log of data for further research and study, since they quantify genuine per-event carbon emission values at today’s grid carbon intensity.

In this report we take a complementary approach, where we project the impact of LCL solutions into the 2030/2050 time horizon, estimating the carbon impact of these solutions in the context of accelerated rollout of LCTs and rapid expansion of renewable and other zero- or low-carbon electricity generation technologies. In doing so, we provide a perspective on the carbon reduction potential from smart LCL solutions in the future electricity system where decarbonisation is a key strategic objective.
3 Scenarios and modelling approach

This section describes the modelling methodology applied to assess the carbon impact of LCL solutions in the future GB electricity system. It also describes the 2030 and 2050 system scenarios that the carbon impact is quantified against.

3.1 Imperial’s Advanced Stochastic Unit Commitment (ASUC) model

Because of the expected rapid expansion of intermittent renewable capacity, in particular wind and solar PV, the uncertainty that needs to be managed in the electricity system will increase significantly. The uncertainty of forecasted wind output on a time scale several hours ahead requires that a much larger volume of reserve is provided to the system in order to absorb the unpredictable output fluctuations.

In such circumstances relying on traditional deterministic analytical tools for power systems cannot capture all the phenomena driven by increased uncertainty. For that reason Imperial has developed the Advanced Stochastic Unit Commitment (ASUC) model [12], which allows for explicitly capturing the probabilistic properties of wind output and their impact on electricity system operation. The following section provides a description of the methodology behind ASUC.

3.1.1 Methodology

The methodology for assessing the carbon impact and wind twinning of LCTs is based on the least-cost annual generation system scheduling approach, capable of considering both the delivery of energy as well as the provision of reserve and frequency regulation services. Generation scheduling determines the commitment and dispatch decisions of generators in a power system considering the need for flexibility and various types of ancillary services. The cost minimisation is subject to various dynamic operating constraints, e.g. start-up times for thermal units. The stochastic scheduling simulation tool developed by Imperial College is designed to provide optimised generation schedules in the light of wind, demand and generator outage uncertainties. Figure 4 provides a schematic illustration of the components of the tool. Wind realisations, wind forecast errors and generator outages are synthesised from models and fed into a scheduling model, which finds the optimal commitment and dispatch decisions given the uncertainties and constraints. The decisions are found using a scenario tree, which represents a discretisation of the range of outcomes of the stochastic variables (e.g. available wind output), with each path through the tree representing a possible outcome or scenario.

Key outputs of the model include the optimal scheduling decisions and generator dispatch, volume of renewable output that needs to be curtailed as well as the corresponding emissions from the electricity system. The model will therefore be able to account for the impact of low-carbon solutions both at the level of modified demand profiles, as well as by considering their potential contribution to providing ancillary services to the system.
3.1.2 Advantages of stochastic scheduling approach in systems with high penetration of intermittent renewables

This model is capable of dynamically scheduling spinning and standing reserve in the system to ensure that a given level of security of supply is maintained at minimum cost. Therefore, operating reserve requirements are endogenously optimised within the model. Since the LCTs can also contribute to reserve provision, optimal scheduling of various types of reserve is critical to understand the impact of LCTs on the system operation. In addition, stochastic scheduling also enables to optimally split the capacity of LCTs between energy arbitrage and ancillary service provision under different system conditions.

Furthermore, the ASUC model also considers the required level of frequency response in the system, taking into account the effect of reduced system inertia at high RES penetrations. Given that intermittent renewable generation will replace conventional generation, the aggregated inertia in the system provided by rotating synchronous machines will decrease, requiring more frequency regulation to maintain the frequency within the statutory limits. If the required frequency regulation is provided only by part-loaded plants, this may lead to RES curtailment and lower operating efficiency of conventional plants, eventually increasing carbon emission. Therefore it is important to take into account of this effect when quantifying the impact of frequency regulation provision from LCTs on the system emission performance. Figure 5 illustrates the inertia-dependent frequency regulation requirement for varying levels of wind penetration in the GB system.

---

7 Although there is a significant body of academic research analysing the potential provision of synthetic inertia by wind turbines (i.e. DFIG generators), in our study wind generation does not provide inertia, which is consistent with future projections adopted in a number of recent studies.
3.2 Scenarios for carbon impact assessment of future GB electricity system

In this section we describe the scenarios used to characterise the GB electricity system in 2030 and 2050 in order to provide a background to evaluate the carbon impact of LCL technologies.

3.2.1 Key sources of information

In this report we use two scenarios from the report on synergies and conflicts in the use of DSR prepared by Poyry [13], Green World and Slow Growth, including the associated generation capacities and demand profiles. The two scenarios are designed to deliver carbon emissions in the order of 100 g/kWh and 200 g/kWh, respectively. Generation background to the two scenarios corresponds to National Grid’s Gone Green and Slow Progression scenarios, respectively. Demand information also includes the assumptions on electrification of transport and heating demand, as specified in the following sections.

The 2050 scenario used in the study is based on a High Renewable scenario from DECC Carbon Plan [14], with fluctuations of hourly demand constructed as in [6].

3.2.2 Scenarios for expected evolution of electricity generation and demand

The assumed generation capacity in the GB system in 2030 and 2050 is presented in Figure 6. Generation capacity in 2030 Green World (GW) scenario is about 140 GW, of which 72.8 GW is RES generation (56.9 GW of wind and 15.8 GW of solar PV). Total installed capacity in 2030 Slow Progression (SP) scenario is around 104 GW, of which 41.7 GW is RES generation (34.4 GW of wind and 6.1 GW of solar PV). For 2050 High Renewable (HR) scenario, there are 226 GW installed generation, 42% of which is contributed by RES capacity. The penetration of RES with respect to meeting annual electricity demand is 31%, 47% and 54% in 2030 SP, 2030 GW and 2050 HR, respectively.
The demand assumptions are shown in Table 1. The base demand (excluding EV and HP demand) is the same for 2030 GW scenario and 2030 SP scenario, with annual consumption 344 TWh and peak demand 59.1 GW. While the EVs and HPs demand is much higher in GW scenario. The base demand increases moderately in 2050 HR scenario, however, the EVs and HPs demand increases more than twice compared with that in the GW scenario.

<table>
<thead>
<tr>
<th>Demand Information for the GB system in 2030 and 2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>2030 Green World (GW)</td>
</tr>
<tr>
<td>2030 Slow Progression (SP)</td>
</tr>
<tr>
<td>2050 High Renewable (HR)</td>
</tr>
</tbody>
</table>

3.2.3 Uptake scenarios for smart low-carbon technologies

EV and HP uptake in 2030 GW and SP scenarios is assumed in line with those used in [13], which correspond to DECC 4th (2013) Carbon Budget Scenarios 4 and 3, respectively.

Uptake of residential dToU and I&C DSR is varied as follows:

- dToU: 25%, 50% and 75%
- I&C DSR: 25%, 50% and 100%

The flexibility of all smart LCTs was assumed as discussed in Section 2.1.
4 Quantitative assessment of carbon impact of smart distribution networks

In this section the methodology described in Section 3.1 is applied to quantify the carbon impact of smart and non-smart LCTs (including EVs, HPs, dToU and I&C DSR) in 2030 and 2050 GB systems. The frequency response capability of EVs and HPs is analysed, as well as the different penetration levels of dToU and I&C DSR. In addition, this section investigates the carbon implications of fully smart cases where the full potential of smart LCTs is used to support system balancing.

4.1 Approach to quantifying the carbon impact of smart LCTs

The carbon impact of smart LCTs is assessed by comparing the annual system emission with and without smart LCTs. The analysed cases are summarized in Table 2. EVs and HPs technologies are assessed by using the given demand profiles with and without flexible operation. In addition, studies regarding their response regulation capability are also carried out. Impacts of dToU and I&C DSR with different penetration levels are analysed. For the fully smart case, all the above LCTs are set at the maximum flexibility level in terms of balancing, while the fully smart balancing & frequency case assumes DSR can contribute to frequency response and provide inertia in the system.

<table>
<thead>
<tr>
<th>Case Studies</th>
<th>Assumptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Non-smart</td>
<td>No smartness/flexibility from LCTs</td>
</tr>
<tr>
<td>2 Smart EV</td>
<td>EVs are flexible with low frequency response capability</td>
</tr>
<tr>
<td>3 Smart EV / FR</td>
<td>EVs are flexible with high frequency response capability§</td>
</tr>
<tr>
<td>4 Smart HP</td>
<td>HPs are flexible without response capability</td>
</tr>
<tr>
<td>5 Smart HP / FR</td>
<td>HPs are flexible with high response capability</td>
</tr>
<tr>
<td>6 dToU</td>
<td>Flexible domestic demand with varying penetrations (25/50/75%)</td>
</tr>
<tr>
<td>7 I&amp;C DSR</td>
<td>Flexible I&amp;C demand with varying penetrations (25/50/100%)</td>
</tr>
<tr>
<td>8 Fully smart: balancing</td>
<td>Maximum flexibility from all DSR for balancing (combined effect of all smart options in case studies 2, 4, 6, and 7, the latter two at the highest penetrations)§</td>
</tr>
<tr>
<td>9 Fully smart: balancing &amp; frequency</td>
<td>Maximum flexibility from all DSR for balancing and provision of response and system inertia (combined effect of all smart options in case studies 3, 5, 6, and 7, the latter two at the highest penetrations)</td>
</tr>
</tbody>
</table>

The results are presented through three different metrics. Firstly, average system emission rate is defined as the ratio of total system carbon emission over the total system demand. The second metric is the incremental carbon emission, which is the ratio of incremental carbon emission caused by EVs/HPs over the corresponding electricity demand. The third metric is carbon emission reduction per unit of energy of “smart” demand, which is calculated as the ratio of total system emission reduction caused by smart LCTs over the corresponding LCTs demand.

---

§ High frequency response capability here refers to the speed of response i.e. denotes EV fleet that is capable of rapidly interrupting (stopping) charging in order to provide frequency regulation.

§ The benefit of fully smart is generally lower than the simple sum of the benefits delivered by individual LCTs due to saturation effects.
4.2 Carbon benefits of smart management of LCTs

4.2.1 Average system emissions
Carbon emissions from today’s electricity system, also reflected in the LCL trial carbon assessment covered in detail in the appendix to this report, are around 450 g/kWh. With the expansion of zero- and low-carbon technologies and retirement of high-emitting plants such as coal, the grid emissions are expected to become massively reduced. Scenarios analysed in this report reflect the decarbonisation of the electricity system, and the objective of case studies presented here is to estimate to which extent LCTs can support an even more ambitious decarbonisation of electricity supply.

In the first step, the annual operation of the system is simulated without any contribution from the LCTs. As shown in the Non-smart case in Figure 9, the average emission rate for the 2030 GW scenario is 115 g/kWh, while due to lower penetration of RES and Nuclear, the emission rate in 2030 SP scenario is around 150 g/kWh. The combination of high penetration of RES, Nuclear and CCS plants in the 2050 HR scenario leads to a highly decarbonised electricity system with the average emission rate at around 48 g/kWh.

After establishing the baseline system carbon performance, we proceed to quantify the carbon impact of each smart technology on the overall system emissions. The results for the 2030 GW scenario are presented in Figure 7. The average system emission rate is reduced by 5 and 8 g/kWh due to smart EVs and smart HPs, respectively, and this is further reduced by 4 g/kWh and 5 g/kWh if smart EVs and HPs can contribute to frequency regulation. Although smart EVs are in general more flexible than smart HPs, the reduction caused by HPs is higher due to higher volume of HP demand in the system. The average system emission rate is also reduced as the uptake of dToU and I&C DSR increases: up to 5 and 6 g/kWh, respectively. In the fully smart balancing case (with dToU and I&C DSR at their highest penetration points), the combination of all smart technologies leads to a reduction in specific emissions of more than 17 g/kWh. The highest reduction however is achieved in the fully smart balancing case where DSR also provides maximum amount of frequency response and inertia; emissions in this case are about 33 g/kWh lower than in the non-smart case, which is almost double the reduction of the fully smart balancing case.

---
Figure 7 Impact of different smart technologies on average system carbon emissions (2030 Green World)

As shown in Figure 8, similar trends are observed in the 2030 SP scenario. However, due to a lower penetration of RES, the carbon impact of smart LCTs is less significant, as only 8 g/kWh emission reduction is observed in the fully smart balancing case, and 10 g/kWh in the fully smart balancing with frequency control. In addition to lower RES penetration, it is also important to point out that the penetrations of EVs and HPs are also lower when compared with the GW scenario. Therefore, the carbon benefits of smart EVs and HPs reduce the most among the smart LCTs when compared to the GW scenario.

Flexible electrified heating seems to have among the highest decarbonisation potentials, but from our Low Carbon London trials it appears to have the lowest flexibility unless heat storage is built in from the outset. The mass of Electric Vehicles in future, dToU and I&C DSR are relatively similar in the scale of their impact. However, the scale of the supply chain challenge is very different in each case: to achieve 25% of I&C DSR is likely to be simpler than achieving shift from all electric vehicles, or shift from 25% of residential customers. The latter are only likely to happen with incentives or directives, whereas progress may be made towards the former within existing supply chains.

Figure 8 Impact of different smart technologies on average system carbon emissions (2030 Slow Progression)

The carbon impact of smart technologies in the 2050 HR scenario is illustrated in Figure 9. Although the electricity sector in this scenario will have already been largely decarbonised by 2050, smart LCTs could effectively further reduce the average emission rate by up to 15 g/kWh in fully smart cases (no
great difference is observed between the balancing case and the one with combined balancing and frequency control). Because of a higher penetration of EVs and HPs than in the other two scenarios, the average emission rate could be reduced from 48 g/kWh in the non-smart case to 38 g/kWh and 36 g/kWh by smart EVs and HPs, respectively. However, the provision of frequency regulation from smart EVs and HPs shows a very small carbon impact due to the fact that the frequency regulation in the non-smart case is provided by low-emitting CCS plants, so the displacement of those, although economically beneficial, does not yield significant improvements in carbon performance.

![Graph showing system average CO2 emissions for different scenarios](image.png)

**Figure 9 Impact of different smart technologies on average system carbon emissions (2050 High Renewables)**

A summary of average system emissions for the three scenarios and for the non-smart and fully smart (i.e. the most optimistic) cases is provided in Table 3. As mentioned before, all of these scenarios assume a significant drop in grid emissions from today’s value of around 450 g/kWh.

<table>
<thead>
<tr>
<th>(in gCO2/kWh)</th>
<th>Non-smart</th>
<th>Fully smart</th>
<th>Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>2030 GW</td>
<td>115.5</td>
<td>82.2</td>
<td>−28.9%</td>
</tr>
<tr>
<td>2030 SP</td>
<td>150.1</td>
<td>139.9</td>
<td>−6.8%</td>
</tr>
<tr>
<td>2050 HR</td>
<td>48.3</td>
<td>34.0</td>
<td>−29.7%</td>
</tr>
</tbody>
</table>

### 4.2.2 Carbon intensity of supplying electrified transport and heat demand

As the transport and heating sector become progressively electrified, additional electricity demand will need to be supplied by the power system, potentially increasing the carbon emissions from the electricity system.\(^{11}\) Figure 10 shows the weighted average carbon intensity of the electricity consumed by EVs and HPs. The intensities of EV and HP demand have been found for non-smart, smart and smart/FR cases, by quantifying grid emissions in each hour during the year and averaging them over the volume of EV or HP demand while using hourly EV or HP demand levels as weighting factors. For each of the cases included in Figure 10 we also present the average system emissions (as in Figure 7 to Figure 9) as vertical error bars.

We observe that in general the carbon intensity in the non-smart cases is higher than the intensity in smart operation cases. We further note that the carbon intensity of HP demand is consistently higher

---

\(^{11}\) For an effective decarbonisation of the overall economy, carbon increases in the electricity sector should be more than offset by carbon savings from the reduced use of fossil fuels in road transport and heating.
than average emission rate of the whole system, regardless of the scenario and the level of smartness. This follows from the fact that HPs operate during winter when demand is generally higher and more expensive and more carbon-intensive generation technologies are used (such as e.g. CCGT and OCGT units). That is why even when HPs follow smart operation strategies and consequently reduce total system emissions, their average emission rate is still above the overall system average. Carbon intensity of EV demand in the non-smart cases is around or slightly above the average system emissions, but when smart EV charging strategies are implemented, the emissions associated with EV demand decline rapidly, also causing a decrease in the total system emissions.

In particular, under the 2030 GW scenario the carbon emission rate of EV demand is reduced from 116 to 105 g/kWh by smart charging, and further reduced to around 99 g/kWh in the case with frequency regulation from EVs. Due to lower relative flexibility associated with smart HP operation (see Sections 2.1.1 and 2.1.2), as well as its seasonal character, the decrease in the carbon emission rate driven by smart HP operation, when expressed per kWh of HP demand, is slower than for smart EVs, but is still able to reduce the emission rate by 14 g/kWh in the case with frequency response provision.

In the 2030 SP scenario, shown in Figure 10(b), similar trends for carbon emission rates of EV and HP demand are observed as in the GW scenario. However, due to the lower penetration of RES and nuclear capacity, the ability of smart EVs and HPs to reduce the carbon emission is not as pronounced as in the GW scenario. In other words, the emission rate, which already starts from a comparably higher level than in the GW scenario (over 150 g/kWh), reduces by only 9 i.e. 5 g/kWh for EV and HP demand, respectively, when fully smart operation is accompanied by FR provision.

![Figure 10 Carbon emission intensity of supplying EV and HP demand for different levels of smartness](image-url)
Finally, the results presented in Figure 10(c) demonstrate the carbon emission rate of EV and HP demand in the 2050 HR scenario. In the non-smart case, the average emission rate of the whole system is rather low (48 g/kWh, as shown in Figure 9), although the carbon emission rate associated with EV and HP demand is slightly higher (57 i.e. 55 g/kWh, respectively). Smart operation strategies reduce the carbon intensity of EVs and HPs to 30 g/kWh for EVs and 38 g/kWh for HPs; both of these figures represent a significant relative reduction from the non-smart cases. We again observe that smart EV charging is more effective in reducing system carbon emissions than smart HP operation – as already discussed, which is primarily driven by the seasonality of HP demand.

4.2.3 Avoided emissions per unit of smart demand

This section estimates the carbon savings driven by the deployment of smart LCTs expressed as annual carbon reduction per unit of “smart” demand. As shown in Figure 11 to Figure 13, all the smart technologies lead to a significant carbon emission reduction per unit demand. These carbon savings in many cases exceed the average system emissions, which means that in some cases the carbon impact of smart technologies is even better than carbon-neutral, i.e. they are able to create a net offset in carbon emissions per unit of smart demand.

In general, smart EVs show the most prominent reduction per unit demand, up to 220 g/kWh in the 2030 GW scenario, and 150 g/kWh in the 2030 SP and 2050 HR scenarios. dToU and I&C DSR show the second and third largest carbon emission reduction effect among the studied LCTs. However, the results suggest as the increase of penetration level, the avoided emission per unit demand reduces. Due to limited flexibility, smart HPs generate the lowest carbon emission reduction per unit demand, but still could reduce the emissions by around 50-100 g/kWh under different scenarios.

![Figure 11 Carbon emission reduction per unit of “smart” demand (2030 Green World)](image)

---

12 Reductions per kWh of dToU and I&C DSR demand have been calculated by dividing the respective carbon savings with only that share of participating residential or I&C load that was flexible, according to the assumptions made in Sections 2.1.3 and 2.1.4. For instance, in the dToU 50% case, the emission savings are divided by 50% x 20% = 10% of total residential demand.
Figure 12 Carbon emission reduction per unit of “smart” demand (2030 Slow Progression)

Figure 13 Carbon emission reduction per unit of “smart” demand (2050 High Renewable)

In the fully smart case, because of the saturation effect, the carbon emission reduction per unit of “smart” demand reaches the lowest value at around 60 g/kWh in the 2030 GW scenario, 40 g/kWh in the 2030 SP scenario and 45 g/kWh in the 2050 HR scenario. These values however almost double when fully smart balancing is combined with frequency response provision.

4.3 Summary of findings

A large number of numerical studies have been run to quantify the carbon benefit of different LCTs over three representative scenarios in the 2030 to 2050 horizon. Table 4 provides a summary of the carbon benefit per unit demand for different LCTs across proposed scenarios, while Figure 14 compares the average system emission rates for non-smart case and fully smart with balancing only and with combined provision of balancing and frequency regulation.

<table>
<thead>
<tr>
<th>LCT</th>
<th>2030 GW (in gCO₂/kWh)</th>
<th>2030 SP (in gCO₂/kWh)</th>
<th>2050 HR (in gCO₂/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EV</td>
<td>92-151</td>
<td>114-218</td>
<td>129-152</td>
</tr>
<tr>
<td>HP</td>
<td>46-78</td>
<td>65-109</td>
<td>58-68</td>
</tr>
<tr>
<td>dToU</td>
<td>99-127</td>
<td>135-161</td>
<td>161-174</td>
</tr>
<tr>
<td>I&amp;C DSR</td>
<td>78-110</td>
<td>103-131</td>
<td>122-155</td>
</tr>
</tbody>
</table>
The results of our studies on carbon impact of smart LCTs suggest the following:

- Carbon benefits of different DSR technologies expressed per unit of smart demand are primarily driven by the flexibility to shift demand and provide frequency regulation.
- Carbon benefits of all LCTs increase if they provide frequency response in addition to smart balancing.
- Carbon benefits are generally more pronounced with higher intermittent RES penetration, but can be limited if the non-renewable generation capacity on the system is mostly zero-carbon (as in the 2050 HR scenario).
- Integration of electrified transport and heating demand is significantly less carbon intensive if smart operation strategies are adopted.
- Irrespective of the carbon scenario, or exactly which sources of DSR are adopted, there seems to be potential to reduce average system carbon emissions by an additional 5 g/kWh.
5 Impact of smart LCTs on renewable integration cost

In this section we investigate the impact of smart LCTs (EVs, HPs, dToU and I&C DSR) on the cost of RES integration in the 2030 and 2050 GB systems. We apply the ASUC model described in Section 3.1 to quantify the cost reductions associated with lower back-up capacity requirements, reduced system balancing cost and reduced CAPEX due to avoided investment in low-carbon capacity to reach the CO₂ target.

5.1 Challenges of RES integration

The UK has a very significant wind power resource that is expected to contribute significantly to the decarbonisation of the electricity system, with almost 12 GW of wind generation already in operation as of November 2014. A key feature of wind as well as solar PV generation is the variability of the primary energy source, which is often referred to as intermittency. Similarly, there has recently been a rapid increase in the number of solar PV installations.

The intermittent nature of wind and solar PV generation creates a number of challenges for system operators, regulators, transmission planners and industry participants. In order to deal with unpredictability and variability of RES, levels of operating reserves and frequency response reserves scheduled by system operators need to increase to ensure that demand and the generation are always balanced. Moreover, any additional generation capacity required to provide “wind or solar firming” for system security reasons can be considered as an additional cost associated with intermittent RES generation.

These system integration impacts need to be assessed in order for the overall system cost of intermittent RES to be quantified. As indicated in Figure 15, the total Whole-System Cost (WSC) of intermittent RES consists of their Levelised Cost of Electricity (LCOE) and the system integration cost of RES. The latter is defined as the total of additional infrastructure and/or operating costs to the system as a result of integrating renewable power generation.

\[
WSC_{RES} = LCOE_{RES} + \text{System Integration Cost}
\]

- Capital costs
- O&M costs
- Generation capacity costs
  (adequacy, emissions target)
- Generation patterns
- Balancing services costs

Figure 15 Whole-system cost of intermittent RES

LCOE considers the capital cost and O&M cost of RES technologies over their project life while the system integration cost of RES includes the system capacity costs associated with capacity needed for

---

security, balancing costs and the impact of the RES output patterns. Other components of system integration cost, not considered in this report, may include transmission and distribution network costs, as well as the cost of network losses; these components would reflect any requirement to reinforce transmission and distribution networks in order to accommodate wind and PV generation. In this report we focus on the capability of smart LCTs to reduce the system integration cost of wind and solar PV generation.

As the system integration cost of RES due to increased requirements for back-up capacity, provision of reserves is significant, it is important to implement new operating approaches that can minimise the integration costs. In this context, we will quantify the benefits of LCT resources trialled in LCL for reducing the system integration cost of wind and solar PV. The benefits will be assessed in the three categories discussed above:

1. **Reduced backup capacity cost.** LCTs have the capability of shifting demand i.e. modifying the effective (net) demand profile seen by conventional generators. If the smart LCTs are operated so that they reduce the net peak demand, this will also reduce the requirement for generation capacity margin in the system while maintaining security of supply. In other words, smart LCTs may improve the capacity value of wind and PV. Reduction in backup capacity cost due to improved capacity value is quantified according to [15].

2. **Reduced balancing operating cost.** This component of the RES integration cost reflects the increased need to provide reserve and response in the system with high RES penetration, as well as the occasional necessity to curtail wind or PV output in order to balance the system (e.g. at times of low demand and high wind or solar output). Smart LCTs have the potential to absorb some of this output that would otherwise be curtailed, while at the same time provide reserve and response services that would otherwise have to be provided by conventional generators at a considerable cost.

3. **Reduced investment cost associated with balancing.** In the context of a specific CO₂ target, reducing the curtailment of wind and PV output by deploying smart LCTs also means that less additional zero- or low-carbon generation capacity will need to be built in order to meet the carbon target. We quantify this component of RES integration cost savings by assuming reduced wind output required less CCS capacity to be built.  

### 5.2 Case studies

The studies are based on the 2030 and 2050 GB system scenarios described in Section 3.2. Assumption for these scenarios can be found in Table 2.

The simulations are firstly carried out to characterise the annual operation of the system as well as necessary wind and PV curtailment without any contribution from DSR (i.e. the non-smart case). After establishing the baseline RES balancing cost, benefits of each DSR technology for RES integration are assessed by comparing the key characteristics of smart and non-smart cases:

---

For instance, a renewable technology generating the highest electricity output during system peak demand would have a lower integration cost than the alternative technology that produces the same output annually, but provides the highest output during off-peak conditions.

In the studies presented here we assume the future investment cost of CCS capacity of £1,313.8/kW, lifetime of 25 years and the discount rate of 10%.
operating cost, backup capacity requirement and wind curtailment. We do not express the baseline integration cost (without LCTs active in the system) given that the focus of the report is on the contribution of smart LCTs trialled in LCL.

In all studies we treat wind and solar PV collectively as intermittent renewable generation, although in the model these two were disaggregated as illustrated at the end of this section.

Figure 16 presents the value of smart LCTs for reducing RES integration cost in the 2030 GW scenario. The same case studies are analysed as in Section 4, and the benefits are expressed as annual integration cost savings (with the three components defined in the previous section) divided by the volume of absorbed annual RES output. We note that the greatest integration cost savings are achieved with smart HP operation, mostly because of the large volume of flexible HP demand assumed in this scenario. Total integration cost savings per individual technology vary between about £1 and £5/MWh. If all smart LCTs simultaneously provide balancing to the system, the savings increase to £8/MWh, while if they are additionally capable of providing frequency response, this increases further to £11/MWh. It is also possible to observe that the three components of RES integration benefits arise in broadly similar proportions.

![Figure 16 Reduced RES integration cost from deployment of smart LCTs (2030 Green World)](image)

Results for the same set of case studies but for the 2030 SP scenario are presented in Figure 17. We observe similar trends as in the 2030 GW scenario, although the benefits tend to be lower. Best-case benefits, when all smart LCTs coexist in the system, vary between £6.4 and £7.6/MWh. We also note that the contributions of dToU and I&C DSR slightly increase, given that the volume of residential and commercial demand is the same, while the volume of RES output is lower than in 2030 GW.
Finally, in Figure 18 we show the RES integration cost savings with smart LCTs in the 2050 HR scenario. The backup component for smart EVs and HPs increases significantly due to the large assumed deployment of these technologies in the 2050 HR scenario. Fully smart cases bring savings of about £10-11/MWh, similar as in the 2030 GW scenario. The balancing CAPEX component in this scenario exceeds those seen in the other two scenarios, as the deployed volume of wind and solar PV, and consequently also of their curtailment, is the greatest. Total integration cost savings for individual technologies varied between £3.8 and £6.5/MWh for EVs and HPs, and between £0.6 and £2.0/MWh for dToU and I&C DSR (savings from these two DSR categories are much lower because the scenario assumes a drastic improvement in energy efficiency and large reduction in residential and commercial electricity demand).

We finally illustrate that if integration benefits are allocated separately to wind and solar generation, the scale and the composition of benefits might vary considerably between these two technologies. To that end, Figure 19 shows that while smart LCTs reduce wind curtailment, as well as aggregate RES curtailment that is dominated by wind due to its size, smart utilisation of LCTs may also lead to higher PV curtailment as part of the overall cost-optimal solution (note that the total curtailment still reduces). This suggests the existence of certain trade-offs, where the flexibility of LCTs is used to absorb wind output even at the expense of slightly increased PV curtailment, as it results in a more cost-efficient solution.
On the example of the 2030 GW scenario, Figure 20 further shows how different components of system integration benefits generated by smart LCT operation may arise in markedly different proportions if these benefits are allocated to wind and solar capacity according to the integration cost driven by these two technologies. Wind capacity dominates the overall RES mix, therefore the integration benefits for wind and total intermittent RES portfolio differ very little. On the other hand, the benefits for PV integration consist almost exclusively of backup cost savings, with the balancing OPEX and CAPEX components almost negligible. As illustrated in the previous figure, this occurs because smart LCT operation is not utilised to reduce PV curtailment, but on the contrary rather allows the PV curtailment to increase in order to use more attractive opportunities to save wind curtailment. Increase in PV curtailment is more than offset by balancing cost savings associated with more efficient system operation, which results in positive although small levels of saving in balancing OPEX and CAPEX categories.

5.3 Average and marginal value of smart technologies
When finding the value of smart LCTs, we distributed their benefits in terms of reduced integration cost across the entire output of intermittent RES generators in a given scenario. It is obvious that if
an additional unit of RES capacity is added onto a system that already has significant RES capacity, the additional integration cost of the added capacity is likely to be higher than the average integration cost of the entire RES portfolio. This is because as more wind and PV are added to the system it becomes progressively more difficult to absorb their output without having to resort to generation curtailment. For the same reason, adding the first few megawatts of RES generation to an electricity system usually results in low integration cost given that the system’s inherent flexibility enables it to absorb wind and PV output fluctuations relatively easily.

Therefore, in addition to average RES integration benefits such as those described in Section 5.2, we also quantify in this study the marginal benefits of smart LCTs, i.e. the reduction of RES integration cost if a small quantity of RES is added to the capacity already existing in each scenario. We first summarise the average benefits for all three scenarios in Figure 21, showing the integration benefits for the two fully smart cases (with and without frequency response provision).

![Figure 21 Average RES integration benefits from deployment of smart LCTs](image)

In contrast to average benefits, we show in Figure 22 the marginal benefits of smart LCT operation when a small quantity of RES capacity is added to the system in 2030 SP, 2030 GW and 2050 HR scenarios. An immediate observation is that the marginal benefits exceed comparable average benefits by a factor of 2 to 3. This suggests that the value of smart LCTs for integrating additional RES capacity in a system that already contains a large share of intermittent renewables is significant. A further conclusion is that decarbonising the electricity system by integrating large amounts of wind and PV capacity can be much more cost-efficient if coupled with smart DSR technologies.
In the two 2030 scenarios the marginal benefit doubles when frequency response is provided by LCTs in addition to balancing, whereas in the 2050 HR scenario the difference between the two fully smart cases is much smaller. We further note that the dominant component of marginal benefit in the 2030 SP scenario is balancing cost (OPEX); in the 2030 GW scenario balancing OPEX savings are commensurate with balancing-driven CAPEX savings. In the 2050 HR scenario the large volume of RES curtailment makes the balancing CAPEX benefits the dominant component.

5.4 Key findings on renewable integration benefits of smart technologies

This section investigated the benefits of LCTs monitored within LCL trials in supporting more efficient integration of intermittent renewable technologies across the three analysed scenarios. From our numerical studies it is possible to draw the following conclusions:

- DSR technologies have a significant potential to support RES integration by reducing: balancing cost, required back-up generation capacity and cost of replacing curtailed RES output with alternative low-carbon technology to achieve the same emission target.
- Penetration of individual DSR technologies i.e. the uptake of e.g. EVs, HPs etc. is an important factor in the value of DSR for RES integration.
- DSR are capable to support cost-efficient decarbonisation of future electricity system by reducing RES integration cost.
- Average RES integration benefits when all smart LCTs coexist in the system vary between £6.4 and £11.4/MWh of absorbed RES output across the three scenarios.
- Marginal RES integration benefit found in our studies is 2-3 times higher than the average benefit, suggesting an increasingly important role for DSR in expanding RES capacity beyond the already high penetrations foreseen in the future.
6 Findings and conclusions

In this report we have presented the results of a large number of case studies carried out in order to quantify the benefits of LCL solutions i.e. smart DSR technologies on the carbon performance and cost of RES integration in the future GB electricity system. All studies were informed by LCL trials.

We find that LCTs are able to deliver measurable carbon reductions primarily by enabling the future, largely decarbonised electricity system to operate more efficiently. Carbon benefits of different DSR technologies, when expressed per unit of smart demand appear to be 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. Irrespective of the carbon scenario, or exactly which sources of DSR are adopted, there seems to be potential to reduce average system carbon emissions by an additional 5 g/kWh.

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 where 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 is significantly less carbon intensive if smart operation strategies are adopted, making a more positive impact on the overall carbon performance of the economy.

It is worth noting that the primary effort of government and regulators will remain on maintaining a trajectory towards a decarbonised generation fleet and the electrification of heat and transport, but the flexibility of LCTs provides a measurable incremental benefit.

In the second set of case studies we have established that DSR technologies have a significant potential to support cost-efficient RES integration by reducing:

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

In that context our studies show that smart DSR technologies are capable of supporting cost-efficient decarbonisation of future electricity system by reducing RES integration cost. Our studies indicate that the penetration of individual DSR technologies i.e. the uptake of e.g. EVs, HPs etc. is an important factor in the value of DSR for wind integration, as it determines the volume of flexible system services that can be provided by DSR technologies.

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


Annex A: Carbon Tool output examples and carbon impact assessment of the LCL trials

This annex contains examples from the Carbon Tool outputs, illustrating the carbon impact of the Low Carbon London trials.

In addition to the carbon projections made in the main body of this report, the carbon footprint of the Low Carbon London trials is also illustrated in this annex. The net carbon effect of each trial area (and in some cases, individual events) was calculated by assessing their impact against Elexon grid mix carbon intensity. Baseline CO2 emissions were calculated prior to each event and the impact of the trial, positive or negative, calculated against this. These trial reports detail the carbon effect of the Low Carbon Trial and underpin the basis for the future scenarios discussed within the main body of this report.

The figures in this annex form a summary of the events for each trial. The complete list with commentary can be found in the Annex B.

Data gathered for each of the trials has enabled carbon reports for the following trial areas to be outputted and as such this annex is organised into following sections:

<table>
<thead>
<tr>
<th>Use Case</th>
<th>Trial Area</th>
<th>Accompanying Learning Report</th>
</tr>
</thead>
<tbody>
<tr>
<td>General Overview</td>
<td>Total carbon footprint</td>
<td>N/A</td>
</tr>
<tr>
<td>Use Case 01, Wind Twinning</td>
<td>Dynamic Time of Use tariff</td>
<td>A1</td>
</tr>
<tr>
<td>Use Case 02, DG</td>
<td>Distributed Generation Monitoring</td>
<td>A7, A9</td>
</tr>
<tr>
<td>Use Case 03, Transport and Heat</td>
<td>Heat Pump and Electric Vehicles</td>
<td>B1, B2, B3, B4, B5</td>
</tr>
<tr>
<td>Use Case 04, Smart Meters</td>
<td>Smart Metering</td>
<td>A1</td>
</tr>
<tr>
<td>Use Case 05, DSM</td>
<td>Industrial &amp; Commercial Demand Side Response</td>
<td>A4, A5, A6, A7 and A8</td>
</tr>
</tbody>
</table>
A.1 General Overview

The total carbon impact of LCL trials is presented in the table below. A positive figure denotes carbon saved against baseline emissions; a negative figure denotes carbon emitted against a baseline emissions.

<table>
<thead>
<tr>
<th>Trial Area</th>
<th>Carbon Impact (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dynamic Time of Use tariff</td>
<td>82,171.00</td>
</tr>
<tr>
<td>Distributed Generation Monitoring</td>
<td>3,001,080.01*</td>
</tr>
<tr>
<td>Heat Pumps</td>
<td>1,910.00</td>
</tr>
<tr>
<td>Electric Vehicles</td>
<td>0.80</td>
</tr>
<tr>
<td>Smart Metering</td>
<td>10,153,000.00*</td>
</tr>
<tr>
<td>Industrial &amp; Commercial Demand Side Response</td>
<td>-166,372.13</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>-82,290.33</strong></td>
</tr>
</tbody>
</table>

* These trials were monitoring only and as such are not included in the total.
A.2 Dynamic Time of Use Tariff

Purpose

The purpose of this section is to provide commentary on the Carbon Impact of the LCL Demand Side Management trials. Data used in this section is available from the Carbon Tool.

This section covers the period from 01/01/2013 – 31/12/2013.

Headline Figures

Annual Impact:

<table>
<thead>
<tr>
<th>Year to Date</th>
<th>Net Carbon Impact (tonnes)</th>
<th>Demand Reduction (kWh)</th>
<th>Demand Increase (kWh)</th>
<th>Demand Reduction %</th>
<th>Demand Increase %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>82.171</td>
<td>161,160.717</td>
<td>-</td>
<td>4.25</td>
<td>-</td>
</tr>
</tbody>
</table>

![Graph showing energy demand and demand difference over time]
February Carbon Impact:

![Carbon Impact Graph]

February Energy Demand:

![Energy Demand Graph]
Example Events

Residential Dynamic ToU: Energy Demand – 7th - 8th February 2013:
Residential Dynamic ToU: Energy Demand – 26th- 27th February 2013:
July Carbon Impact:

July Energy Demand:
Assumptions and Limitations

The speculations made in this section are merely points of interest in the data that may lead to areas for more detailed research. The scope of data for a month does not allow any significant conclusions to be drawn from single events, but the number of participants in the trial should mean that patterns seen here are genuine.

Figures are sometimes given to a number of decimal places. This is due only to the same accuracy being used throughout out the data gathering and calculation process. It in no way indicates that all the data is precise to this degree. There are many factors involved in the estimation of carbon impacts which mean that only the general positive and negative trends of data are significant, not individual figures.

Carbon Impact

One of the aims of a dynamic ToU tariff relating to Carbon Footprint would be to encourage users to shift demand to times where the overall grid generation was less carbon-intensive. However, this trial cannot show the carbon impact of doing this as the ToU tariff interventions do not correspond to actual times of high and low grid carbon intensity.
Demand Difference

This trial is showing a significant reduction in demand in the Trial group over that of the Control group. While the data is scaled to give equivalent use for each group, the difference shown cannot be purely attributed to the effect of the Dynamic ToU tariff.

There may well be an inherent selection bias in the Trial group as this group is made up of people who actively signed up for a trial whereas the control group are just normal users who did not.
A.3 Distributed Generation

<table>
<thead>
<tr>
<th>Site</th>
<th>kW</th>
<th>Monitoring Period</th>
<th>kg CO₂ footprint</th>
</tr>
</thead>
<tbody>
<tr>
<td>DR005</td>
<td>2000-2400* CHP</td>
<td>01/06/13 – 31/8/13 01/12/13 – 28/02/14</td>
<td>944,434.974</td>
</tr>
<tr>
<td>DR029</td>
<td>1200-1500** CHP</td>
<td>01/06/13 – 31/8/13 01/12/13 – 28/02/14</td>
<td>1,546,763.475</td>
</tr>
<tr>
<td>DR079</td>
<td>195 CHP</td>
<td>01/12/13 – 28/02/14</td>
<td>257,297.217</td>
</tr>
<tr>
<td>TOTAL</td>
<td>5395-6095</td>
<td>N/A</td>
<td>3,001,080.007</td>
</tr>
</tbody>
</table>

* 2000kW in the summer trial, 2400kW in the winter trial.

** 1200kW in the summer trial, 1500kW in the winter trial.

DR005

December 2013:
A.4 Heat Pumps

**Purpose**

This trial contains 19 sites in which heat pumps were fitted to replace gas central heating. Data from two sources was gathered, the Energy Savings Trust (EST) and Passiv Systems (Passiv).

Electricity consumption of the heat pumps was measured over a period around February 2014.

The carbon footprint of heat pump electricity consumption is calculated half-hourly using the grid generation carbon intensity for this period and the kWh consumed by the heat pumps.

A half-hourly baseline carbon footprint is estimated using:

- A heat pump Coefficient of Performance (CoP) of 2.7 (Source: UKPN)
- An efficiency for a condensing gas boiler of 95% (Source: UKPN)
- A kg CO₂ / kWh carbon intensity for Natural Gas of 0.18483 (Source: DECC)

The above are used to calculate a carbon footprint for the equivalent use of natural gas to provide the same heating as observed for the heat pump.

From these two carbon footprints, a half-hourly carbon impact is calculated. A positive impact means that the heat pump generates less CO₂ than the equivalent gas central heating. This impact would be highest when the grid mix has low carbon intensity.

**Trial Totals**

<table>
<thead>
<tr>
<th>Site</th>
<th>Heat Pump Carbon (kg)</th>
<th>Baseline Carbon (kg)</th>
<th>Carbon Impact (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1,284</td>
<td>1,376</td>
<td>92</td>
</tr>
<tr>
<td>2</td>
<td>6,083</td>
<td>6,520</td>
<td>437</td>
</tr>
<tr>
<td>3</td>
<td>1,075</td>
<td>1,147</td>
<td>72</td>
</tr>
<tr>
<td>4</td>
<td>1,075</td>
<td>1,147</td>
<td>72</td>
</tr>
<tr>
<td>5</td>
<td>3,432</td>
<td>3,635</td>
<td>203</td>
</tr>
<tr>
<td>6</td>
<td>1,724</td>
<td>1,838</td>
<td>114</td>
</tr>
<tr>
<td>7</td>
<td>670</td>
<td>719</td>
<td>49</td>
</tr>
<tr>
<td>8</td>
<td>1,147</td>
<td>1,223</td>
<td>77</td>
</tr>
<tr>
<td>9</td>
<td>5,346</td>
<td>5,613</td>
<td>267</td>
</tr>
<tr>
<td>10</td>
<td>590</td>
<td>612</td>
<td>22</td>
</tr>
<tr>
<td>11</td>
<td>1,906</td>
<td>2,034</td>
<td>127</td>
</tr>
<tr>
<td>12</td>
<td>686</td>
<td>739</td>
<td>54</td>
</tr>
<tr>
<td>13</td>
<td>937</td>
<td>1,006</td>
<td>68</td>
</tr>
<tr>
<td>14</td>
<td>988</td>
<td>1,021</td>
<td>32</td>
</tr>
<tr>
<td>15</td>
<td>2,012</td>
<td>2,078</td>
<td>66</td>
</tr>
<tr>
<td>16</td>
<td>no data</td>
<td>no data</td>
<td>no data</td>
</tr>
<tr>
<td>17</td>
<td>924</td>
<td>972</td>
<td>47</td>
</tr>
<tr>
<td>18</td>
<td>882</td>
<td>911</td>
<td>29</td>
</tr>
<tr>
<td>19</td>
<td>1,086</td>
<td>1,166</td>
<td>81</td>
</tr>
<tr>
<td>EST Total</td>
<td>22,426</td>
<td>23,831</td>
<td>1,405</td>
</tr>
<tr>
<td>Passiv Total</td>
<td>9,420</td>
<td>9,925</td>
<td>505</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>31,846</strong></td>
<td><strong>33,756</strong></td>
<td><strong>1,910</strong></td>
</tr>
</tbody>
</table>
The overall trial shows a positive carbon impact, meaning that the heat pumps generated less CO₂ than the estimated baseline gas central heating.

**Event Example**

**Site 11:**

```
<table>
<thead>
<tr>
<th>Date</th>
<th>Baseline Emissions</th>
<th>Carbon Emissions</th>
<th>Carbon Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>04 Feb</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>06 Feb</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>08 Feb</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
```

The data for site 11 shows a positive carbon impact on most days in February but negative on the 18th February.

Comparing the grid mix and intensity for the 18th (negative carbon impact) and 23rd (positive carbon impact) of February shows a difference in the grid carbon intensity, mainly due to a difference in the proportion of wind generation:
18th February – High grid carbon intensity:

![Graph showing high grid carbon intensity on 18th February]

23rd February – Low grid carbon intensity:

![Graph showing low grid carbon intensity on 23rd February]
Assumptions and Limitations

The baseline for calculation of a carbon impact for the Heat Pump trial is created on the following assumptions.

1. That the CoP of the heat pump units is 2.7 and that each house would therefore require 2.7 times the kWh used by the heat pump to heat the property to the same degree and at the same time using conventional gas central heating.
2. The baseline gas heating would be a condensing boiler with 95% efficiency. Therefore the 2.7 is divided by 0.95 to give $kWh_{gas} = kWh_{HP} \times 2.84$.
3. The carbon footprint for the heat pump for each half-hour is the kWh for that HH multiplied by the grid carbon intensity (kg CO₂ / kWh) for that HH.
4. The carbon footprint for the baseline gas heating for each half-hour is the estimated kWh for that HH multiplied by the carbon intensity for gas (0.18483 kg CO₂ / kWh) as sourced from Annex 1 of the DECC GHG Conversion Factors 2012.
5. The carbon impact is the difference between the heat pump carbon footprint and the baseline carbon footprint for each HH.

The methodology for estimating a baseline carbon footprint has been suggested by UKPN as a way of creating an indicative carbon impact for this trial, given the nature of the trial performed. It does not imply that the carbon impact reported is a definitive value for specific times and sites in the trial.
A.5 Electric Vehicles

Purpose

The purpose of this section is to provide commentary on the Carbon Impact of the LCL Electric Vehicles (EV) Trial in which short term (~5 minutes) turndowns of EV charging posts were employed to relieve demand on the local grid at certain peak times.

48 EV charging posts, each with a 3 kW output were involved in the trial.

At times determined by the grid load, between one and three of these posts were switched off for a period of approximately 5 minutes, resulting in a shed of 3, 6 or 9 kW respectively.

The turndown events occurred between 29/12/2013 and 08/02/2014.

The chargepost users would not have noticed a significant difference except that, for each turndown, an additional 5 minutes charging would have been needed to deliver the total kWh value required to recharge the vehicle.

A carbon impact can be estimated as follows:

1. Calculate the carbon footprint that would have occurred had the posts not been turned down. This relates to the grid carbon intensity at the time of the turndown.
2. Assume that the displaced charging time required took place at average grid carbon intensity for the trial period and calculate a carbon footprint for this displaced electricity use.
3. The carbon impact will be positive if the turndown events occurred at periods of higher than average grid carbon intensity and negative if they occurred at period of lower than average grid carbon intensity.

Trial Totals

Carbon Footprint

The following graph shows the actual carbon footprint for each turndown event (had electricity been consumed) next to the average carbon footprint for that consumption:
It can be seen from this that the majority of turndown events occurred at times of higher than average grid carbon intensity.

**Carbon Impact**

The following graph shows the actual carbon impact implied by the above graph.
This confirms that on all but 6 days the impact was wholly positive. Where both positive and negative are shown for a day, this indicates more than one intervention with opposite results.

The numerical figures for the trial overall are as follows (all in kg of CO₂):

<table>
<thead>
<tr>
<th>Turndown Carbon Footprint (saved)</th>
<th>Average Carbon Footprint (shifted)</th>
<th>Carbon Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>23.244</td>
<td>22.444</td>
<td>0.8</td>
</tr>
</tbody>
</table>

So the data shows that a small positive carbon impact may have been produced by turning down the EV posts at the times chosen in this trial.

**Assumptions and Limitations**

It is assumed that:

- The output of a post is a constant 3 kW (except when switched off).
- The post is completely switched off when turned down.
- The turndown durations were five minutes, equivalent to 0.25 kWh consumption.

It is also assumed that the demand is shifted from the turndown period to a period of average grid intensity. Since it is not known that this is the case, the carbon impact cannot be taken as definitive, only indicative of a likely type of impact for this trial, given that it transpired that the turndown events mainly occurred in higher than average periods of grid intensity.
A.6 Smart Metering

Purpose

The purpose of this section is to provide commentary on the Carbon Impact of the LCL Demand Side Management trials. Data used in this section is available from the Carbon Tool.

This section covers the period from 01/01/2013 – 31/12/2013.

Headline Figures

Annual Impact:

<table>
<thead>
<tr>
<th></th>
<th>Smart Metering Carbon Footprint (tonnes CO₂)</th>
<th>Energy Demand (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January to December 2013</td>
<td>10,153</td>
<td>19,862,458</td>
</tr>
</tbody>
</table>

This graph shows the total Smart Metering carbon footprint for each month for 2013.
Event Examples

February 2013, Carbon Footprint:

![Graph of Carbon Footprint](image)

**ACORN Key:**
- ACORN1 – Wealthy Achievers
- ACORN2 – Urban Prosperity
- ACORN3 – Comfortably Off
- ACORN4 – Moderate Means
- ACORN5 – Hard Pressed
Energy Demand:

![Energy Demand Chart]

**Assumptions and Limitations**

It is assumed that the proportions of households in the various ACORN groups reflects the actual population demographic of the study area, in this case with ACORN2 being the dominant group.
A.7 Industrial and Commercial Demand Side Response

Purpose

The purpose of this section is to provide commentary on the Carbon Impact of the LCL Demand Side Management trials for Industrial and Commercial sites. Data used in this section is available from the Carbon Tool. Both generation and turndown sites are represented in this section.

Headline Figures

<table>
<thead>
<tr>
<th>Response Type</th>
<th>Summer</th>
<th>Winter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generation</td>
<td>9.209181</td>
<td>1.845919</td>
</tr>
<tr>
<td>Turndown</td>
<td>-109.508</td>
<td>-67.9191</td>
</tr>
</tbody>
</table>

Event Examples

DR001, 2 MW diesel generator. Intervention 19/04/2013 13:00 –15:00

<table>
<thead>
<tr>
<th>Carbon Impact (kg)</th>
<th>Generation (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-648.557</td>
<td>5116.579</td>
</tr>
</tbody>
</table>
DR005, 2.4MW CHP. Intervention 20/06/2013 12:00 –14:00

<table>
<thead>
<tr>
<th>Carbon Impact (kg)</th>
<th>Generation (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-8716.703</td>
<td>56045.515</td>
</tr>
</tbody>
</table>

![Graph showing CO2 emissions and carbon impact over time.](image1)

![Graph showing energy generation and generation difference over time.](image2)
DR053 – 150kW turndown site. Intervention 15/01/2014 10:35 – 11:35

<table>
<thead>
<tr>
<th>Intervention Carbon Impact (kg)</th>
<th>Intervention Demand Difference (kWh)</th>
<th>Day Carbon Impact (kg)</th>
<th>Day Demand Difference (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>58.331</td>
<td>-116.558</td>
<td>-401.884</td>
<td>766.049</td>
</tr>
</tbody>
</table>

![Carbon Impact Graph]

DR042, 800kW turndown site. Intervention 13/08/2013 13:00 – 14:00

<table>
<thead>
<tr>
<th>Intervention Carbon Impact (kg)</th>
<th>Intervention Demand Difference (kWh)</th>
<th>Day Carbon Impact (kg)</th>
<th>Day Demand Difference (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>457.332</td>
<td>-942.822</td>
<td>879.382</td>
<td>-1792.371</td>
</tr>
</tbody>
</table>

![Graph showing carbon impact and demand difference over time](image-url)
Assumptions and Limitations

The carbon emissions for the generation assets in this trial were calculated using DECC’s ‘GHG Conversion Factors 2012 Annex 1.’

The carbon emissions for turndown assets in this trial were calculated against baseline demand and it was assumed that demand patterns are similar at the intervention site on previous days of the same type (i.e. weekdays). The calculations are made using the methodology derived from the EnerNOC white paper “The Demand Response Baseline” 2011. This is consistent with the method used for settlement by UK Power Networks.

Carbon Impact figures are given to three decimal places but this is in no way an indication of accuracy, it is merely of a reflection of the format of the input consumption data. As several assumptions go into calculation of carbon values, all carbon figures should be seen as indicative, not as exact values. Energy Demand data is, however, as originally measured.
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>DNO Guide to Future Smart Management of Distribution Networks</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>Residential Demand Side Response for outage management and as an alternative to network reinforcement</td>
</tr>
<tr>
<td>A2</td>
<td>Residential consumer attitudes to time varying pricing</td>
</tr>
<tr>
<td>A3</td>
<td>Residential consumer responsiveness to time varying pricing</td>
</tr>
<tr>
<td>A4</td>
<td>Industrial and Commercial Demand Side Response for outage management and as an alternative to network reinforcement</td>
</tr>
<tr>
<td>A5</td>
<td>Conflicts and synergies of Demand Side Response</td>
</tr>
<tr>
<td>A6</td>
<td>Network impacts of supply-following Demand Side Response report</td>
</tr>
<tr>
<td>A7</td>
<td>Distributed Generation and Demand Side Response services for smart Distribution Networks</td>
</tr>
<tr>
<td>A8</td>
<td>Distributed Generation addressing security of supply and network reinforcement requirements</td>
</tr>
<tr>
<td>A9</td>
<td>Facilitating Distributed Generation connections</td>
</tr>
<tr>
<td>A10</td>
<td>Smart appliances for residential demand response</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Distributed Generation and Demand Side Response</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>B1 Impact and opportunities for wide-scale Electric Vehicle deployment</td>
<td></td>
</tr>
<tr>
<td>B2 Impact of Electric Vehicles and Heat Pump loads on network demand profiles</td>
<td></td>
</tr>
<tr>
<td>B3 Impact of Low Voltage - connected low carbon technologies on Power Quality</td>
<td></td>
</tr>
<tr>
<td>B4 Impact of Low Voltage - connected low carbon technologies on network utilisation</td>
<td></td>
</tr>
<tr>
<td>B5 Opportunities for smart optimisation of new heat and transport loads</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Electrification of Heat and Transport</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>C1 Use of smart meter information for network planning and operation</td>
<td></td>
</tr>
<tr>
<td>C2 Impact of energy efficient appliances on network utilisation</td>
<td></td>
</tr>
<tr>
<td>C3 Network impacts of energy efficiency at scale</td>
<td></td>
</tr>
<tr>
<td>C4 Network state estimation and optimal sensor placement</td>
<td></td>
</tr>
<tr>
<td>C5 Accessibility and validity of smart meter data</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Network Planning and Operation</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>D1 Development of new network design and operation practices</td>
<td></td>
</tr>
<tr>
<td>D2 DNO Tools and Systems Learning</td>
<td></td>
</tr>
<tr>
<td>D3 Design and real-time control of smart distribution networks</td>
<td></td>
</tr>
<tr>
<td>D4 Resilience performance of smart distribution networks</td>
<td></td>
</tr>
<tr>
<td>D5 Novel commercial arrangements for smart distribution networks</td>
<td></td>
</tr>
<tr>
<td>D6 Carbon impact of smart distribution networks</td>
<td></td>
</tr>
</tbody>
</table>