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Dear Nisha,

Consultation on the Successful Delivery Reward Applications for Low Carbon Networks Fund: *Low Carbon London*

Low Carbon London (LCL) has been a highly ambitious and innovative project, trialling and demonstrating a wide range of potential smarter approaches to investing in and operating the distribution network and supporting cost effective evolution to low carbon future in the coming decades.

Imperial College London, formed dedicated *Learning Laboratory* to support the design and analysis of pioneering trials conducted in LCL project. These included:

- One of the UK's largest smart meter trials to date, designed to study the potential of dynamic time-of-use tariffs in supporting distribution network constraint management and supply following services in supporting system balancing at the national level in the presence of increasing variable renewable generation penetration;
- The most extensive trial of Industrial and Commercial (I&C) demand side response (DSR) carried out in the UK to date;
- Trials of electric vehicles (EV) to better understand domestic and commercial EV usage patterns and their potential impact on the network. A combination of residential and commercial charging data, driving pattern logs and charging post data also makes this one of the UK's largest such trials;
- Measurements gathered from equipment installed within Engineering Instrumentation Zones (EIZs) to enable dynamic system state estimation and provide more detailed data for other models developed for the project;
- The LCL investigated, for the first time, the impact of low carbon technologies on distribution network power quality performance, which is informing discussions regarding the future evolution of power quality standards;

- Extensive analysis of the data gathered in the above trials, resulting in a comprehensive series of publications supporting effective dissemination of the project findings to DNO community, energy consumers, and wider energy industry and government organisations.

Smart Meters and Dynamic Time-of-Use

The most prominent achievement of LCL involved a pioneering large-scale trial of a dynamic time-of-use (dToU) electricity tariff that provided radically new insights into the contribution of the domestic sector towards a cost effective integration of low carbon generation and demand technologies in future distribution networks. Nearly 6000 electricity meters have been installed in residential buildings across the UK Power Networks LPN area of the London distribution network. The installation of these meters and the communication of demand profiles and data transit to the Operational Data Store through the Learning Lab have been validated using a suite of developed advanced software and visualization tools.

In the context of the UK government's plan to roll-out smart metering by 2020, our analysis demonstrated that a suitably designed dToU scheme can support a cost effective transition to a low carbon energy future, while providing the opportunity for consumers to achieve significant savings in their energy bills. The focus of the trial analysis has been the quantification of the potential value of residential demand side response (DSR) to both the local distribution network and the national energy system. Regarding the former, the value of DSR lies in providing distribution network constraint management (CM) and displacing or deferring costly network reinforcements. Concerning the national energy system, supply following (SF) services would contribute to system balancing, supporting the cost effective integration of renewable generation and the achievement of the carbon reduction targets. In contrast with previous research projects, these two value streams have been examined in unison rather than in isolation, identifying relevant conflicts and synergies that are crucial for unlocking the full potential of DSR in future systems.

Apart from the quantification of dToU-enabled DSR, in depth social science based analysis revealed strong acceptance and support for the dToU scheme by the participating consumers, with a particular recognition of the educational role of the scheme, especially for young household members.

Other forms of DSR examined by the LCL project include smart domestic appliances, electric vehicles (EV) as well as industrial and commercial (I&C) DSR.

Electric Vehicles

One of the largest EV trials to date in Great Britain has been carried out within LCL project, combining collection of charging data corresponding to residential and commercial vehicles, logging of driving patterns and monitoring of public charging stations. Key information recorded included active power for charging, timing and duration of charging events and the energy required by EVs during charging events. 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 or on this scale. In particular, it was seen that uncontrolled EV charging led to high peaks in demand, broadly coincident with existing system peak demand. A very regular diversity effect was also seen, meaning that the diversified peak demand per vehicle was less than 30% of that for a single vehicle. This

analysis, based on evidence gathered in the LCL EV trial, has demonstrated that there will be significant opportunities for adopting smart charging approaches in order to ensure an efficient integration of electric mobility.

Industrial and Commercial Demand Side Response

In the case of I&C DSR, LCL has pioneered the development of formal contractual arrangements for the provision of generation-led and demand-led DSR services by industrial and commercial users to the DNO. I&C DSR trials were designed to relieve network congestion during peak demand periods and the measurement of users' compliance has revealed that, for most cases, the I&C resources performed as requested. Comprehensive analysis of I&C trial data has also shown that current practice in measuring I&C DSR responses may be improved by adapting measurement methods to the context of constraint management in distribution networks. It also illustrated the potential impact of common mode failure in I&C DSR. Particular emphasis has been given to optimising the response of a portfolio of I&C DSR participants in order to reduce or even eliminate the well-known payback (or take-back) effect. A novel bottom-up physical model of buildings has also been developed for LCL to assess and analyse their potential DSR capability. This model has produced robust results, closely replicating building load for separate DSR events.

Smart Domestic Appliances

In the case of smart domestic appliances, the project has focused on the "wet" appliance category, including washing machines, dishwashers and tumble dryers, which are responsible for a significant share of residential electricity consumption while at the same time offer best opportunities for demand shifting. The impact of optimising wet appliance operation has been evaluated using the information on appliance ownership collected through the comprehensive LCL household survey.

Power Quality Performance of Low Carbon Technologies

LCL project investigated, for the first time, network wide power quality performance of connecting low carbon technologies, including PV generation, EVs and Heat Pumps (HPs). Trials conducted in the Engineering Instrumentation Zones demonstrated that if a large number of LCTs are connected, although individually compliant with the standard, the combined effect could lead to harmonic voltage distortions that could exceed the planning standard G5/4-1. The trials demonstrated that low-order harmonics would be of particular concerns in case of HPs, while EV and PV technologies are found not to create harmonic pollution. This work is informing discussions regarding the future development of power quality standards.

Quantifying the Benefits of Smart Grid Technologies and Methods

A significant part of our efforts has focused on developing suitable analytical frameworks for the quantification of the effects of a large-scale roll-out of DSR on the operation and planning of distribution networks. By using LCL trial data, we have demonstrated the importance of multi-period DSR scheduling in efficiently supporting network operation and reducing peak demand. This is because efficient peak demand management requires DSR control in the hours before and after the peak occurs, accounting for payback effects. With respect to the planning of distribution networks, Imperial's Load-Related Expenditure (LRE) model has been applied, using data from the LCL trials, 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.

Analysis identified potential gross benefits of about £280m by 2025 and £1400m by 2050 for a scenario in which smart technologies are fully implemented.

Planning Under Uncertainty
Novel stochastic optimisation and minimum-regret approaches, developed for LCL, have demonstrated the value of DSR in providing flexibility for dealing with the undeniable uncertainty regarding the future evolution of demand and generation in distribution networks. Specifically, DSR is found to hold significant option value in postponing capital intensive network reinforcements until more information regarding future evolution pathways becomes available. This work demonstrated the need for update of commercial and regulatory framework to facilitate uptake of cost effective solutions to deal with uncertainty.

Carbon Impact of Smart Distribution Networks
The implications of deployment of the low-carbon technologies (LCTs) and solutions studied in Low Carbon London on reducing carbon emissions and managing integration cost of intermittent renewable generation have been quantified. Analysis clearly demonstrated that a very significant carbon and cost reductions from smart control of LCT would be possible to achieve. Integration of electrified transport and heating demand would be significantly less carbon intensive if smart operation strategies were adopted.

Distribution System State Estimation
In addition to smart DSR solutions, LCL investigated and analysed the performance and potential benefits of the application of Distribution System State Estimation (DSSE). Measurements carried out within Engineering Instrumentation Zones (EIZs) of LCL have demonstrated that the developed prototype DSSE, through a limited number of optimally placed sensors, could robustly estimate voltage and power flows in High Voltage distribution networks. This work presents one of the pioneering efforts in examining the role and possible application of DSSE in the future distribution networks in the UK. The developed model can be used to optimize the type and location of measurements that 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.

Academic Dissemination
A significant number of academic papers, derived directly from LCL findings, have already been written or are in preparation for presentations at key conferences and publication in internationally leading journals.

In summary, Low Carbon London has been highly successful, both in showing that large-scale trials of smart grid technologies and methods are practicable and in gaining fundamentally new insights through analysis of data from these pioneering trials. The high quality of the project outcomes has gained very significant recognition at both national and international level, while the outputs of the LCL demonstrated good value for the end consumers.

Yours sincerely

Prof Goran Strbac