

Unlocking New Sources of Flexibility

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Unlocking New Sources of Flexibility

CLASS: The World's Largest Voltage-Led Load Management Project

By Andrea Ballanti, Luis (Nando) Ochoa, Kieran Bailey, Steve Cox

The significant growth of wind and photovoltaic generation seen in many countries around the world will soon challenge the ability of Transmission System Operators (TSOs) to guarantee the security of supply. To cope with such future low-carbon electricity systems it is therefore imperative to increase the portfolio of flexibility sources in a cost-effective and sustainable manner. This is likely to require exploring solutions beyond the use of traditional players connected at higher voltages such as fast-acting generation plants or large customers.

The management of loads at lower voltages has the potential to play a key role in the provision of short-term flexibility by reducing demand for small periods (≤ 60 min) at times needed by the TSO (e.g., for balancing purposes), the Distribution Network Operator - DNO (e.g., to reduce asset congestion), or even the customers themselves (e.g., to react to time-of-use tariffs). Although numerous load management (LM) schemes have been investigated and some even implemented, particularly focusing on reducing or shifting demand, this source of flexibility still remains largely unexploited due to practicality and scalability issues. Typical LM schemes require engaging directly with customers (e.g., providing price signals, remotely controlling specific appliances, etc.) and this in itself is a major barrier when millions of customers and devices are needed to provide meaningful volumes of flexibility to the TSO - the cost and complexity involving the communication and control infrastructure might be prohibitive. One way of unlocking this source of flexibility, without directly involving thousands or millions of customers, is to exploit the positive correlation between supplied voltage and demand. Permanent energy efficiency measures reduce voltages as much as possible (commonly known as Conservation Voltage Reduction - CVR). DNOs, however, could provide a new source of flexibility by controlling existing voltage regulation devices only when and to the extent required by the TSO - an active, flexibility-driven approach able to support the electricity system.

This article presents the large-scale Smart Grid project "Customer Load Active System Services (CLASS)" run by the UK DNO Electricity North West Limited (ENWL) from 2014 to 2016 and funded by the Low Carbon Networks Fund. CLASS proposed and implemented an innovative voltage-led LM scheme which was demonstrated to be both *practical* and *scalable*, and that saw, among other stakeholders, National Grid (the UK TSO) and ENWL joining forces for the deployment and test of such an approach. The article first introduces the basic concepts of the project, followed by a description of the main infrastructure adopted for its implementation. Then, the potential benefits arising from the regional and national scale deployment of the scheme are presented. Finally, the article discusses regulatory aspects that might enable DNOs to play a more active role in the provision of flexibility in future low-carbon electricity systems.

1. The CLASS Project: Managing Demand, Not Customers

The CLASS project proposes an innovative LM scheme in which DNOs can reduce customer demand for short periods (e.g., 15, 30, 60 min), at the time and to the extent required by the TSO, by controlling the supplied voltage using the on-load tap changer (OLTC) of *primary substation* transformers. This so called voltage-led LM scheme has as key advantages its practicality, as it relies almost entirely on existing infrastructure (the OLTC is a common asset in distribution networks around the world) reducing complexity and cost, and its scalability, as it can unlock flexibility from thousands or millions of customers by only controlling a limited number of points (primary substations).

The voltage-led LM scheme proposed in CLASS was successfully demonstrated with field trials involving 60 primary substations, i.e., more than 350,000 customers. This project, arguably the largest voltage-led LM trial in the world, considered not only the technical aspects but also the social, environmental, and economic implications, resulting in comprehensive learning useful for DNOs, TSOs, and regulators willing to explore this source of flexibility. Table 1 presents a factsheet with key aspects of the project.

Table 1 Factsheet of the CLASS Project

| | | |
|---|---------------------------------------|---|
| Total Cost US\$ 12m* | Primary Substations 60 | Measurements Phase V, I, P, and Q (up to 1s resolution) |
| Project Length 2 years | Customers Involved 350,000+ | TSO → DNO Comms Infrastructure ICCP Link, VF Line |
| Project Partners DNO: ENWL, TSO: National Grid, Academia: The University of Manchester, Others: Siemens, General Electric, Impact Research, WSP Parson Brinckerhoff | Customer Interviews 1,300+ | Areas of Study Engineering, Social Sciences, Environment, Economics |

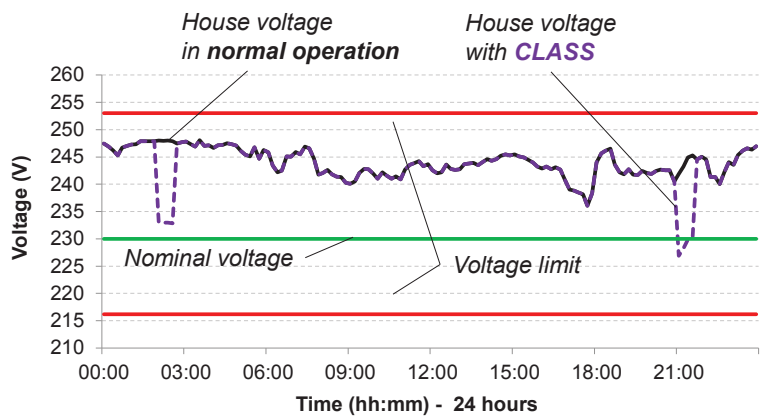
*All the value in this article are reported adopting the following conversion rate: GBPE1→ US\$1.22

1.1. Reducing Voltages To Reduce Demand

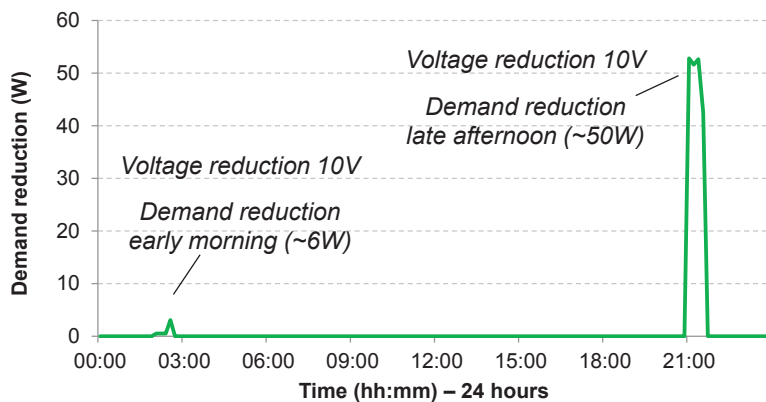
Load undergoes a reduction in demand, although to different extents depending on its type (e.g., resistor, induction motor, fluorescent lamp, etc.), when the supplied voltage is reduced – in other words, there is a positive correlation between them. For instance, if the supplied voltage of a kettle (which can be considered as a resistor) is reduced by 2%, the corresponding demand will reduce by 4%; if it was a compact fluorescent lamp (CFL, which draws the same current constantly) this demand reduction would be 2%.

However, in practice, customers use different types and number of appliances throughout the day resulting in a time-varying composition (in terms of load type). Consequently, although a reduction in the supplied voltage is expected to trigger a reduction in demand, its magnitude will largely depend on the period in which this takes place. This concept is illustrated in Figure 1 where, for

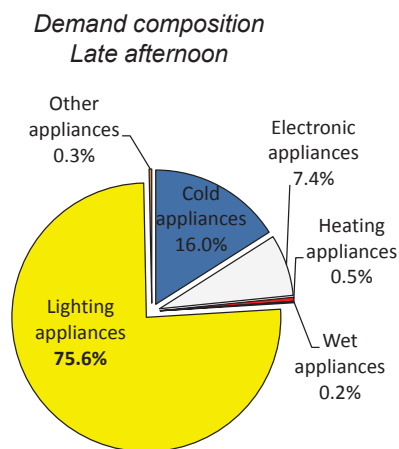
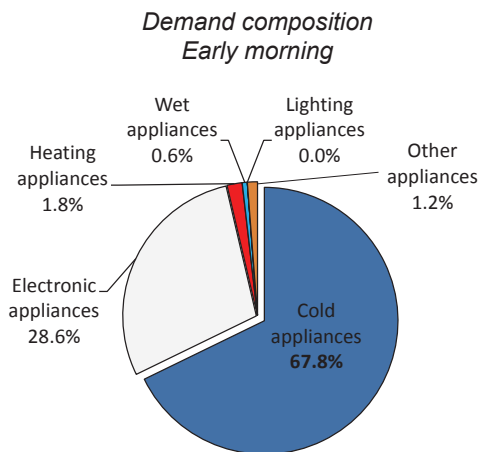
simplicity, the supplied voltage of one house (top, UK values) and the corresponding power consumption (middle) are shown when a voltage reduction of 10V is applied during two half-hour periods: one early in the day (at 2am) and one late (at 9pm).



A supplied voltage within statutory limits



Demand reduction changes in time → time-varying source of flexibility



The demand composition changes in time

Figure 1 Illustration of time-varying aspects when reducing voltages

In Figure 1 (middle), we see that during the early part of the day a reduction of less than 10W was achieved, in contrast to 50W later in the day. This is not only because of different demand volumes (more demand at 9pm than at 2am) but also because of significantly different load compositions. Indeed, as can be seen from the example in Figure 1 (bottom), more responsive appliances (e.g.,

lighting) dominate the demand at 9pm compared to less responsive ones (e.g., freezers, refrigerators) which are the main component at 2am.

Hence, in the context of a voltage-led LM scheme aimed at providing a demand reduction exclusively when, and to the extent, required by the TSO, the assessment of the time-varying (daily and seasonal) demand composition is a major challenge that must first be addressed. This requires the development of time-varying load models that define the mathematical relationships between voltages and demand of any load, including the aggregation of thousands of customers downstream from a given point in a network.

Different from a CVR scheme, commonly aimed at introducing at all times the largest voltage reduction possible to achieve energy savings, a flexibility-driven voltage-led LM scheme needs to quantify the potential demand reduction throughout the day so that it can provide estimates of the available flexibility to the TSO. The second challenge is therefore to estimate how much demand reduction could be achieved at different periods whilst always maintaining end customer voltages within statutory limits.

It is worth highlighting that loads (appliances) are designed to operate within a statutory range of voltages. This is because supplied voltages, in practice, are subject to daily and seasonal fluctuations as a result of changing demand and generation, as well as the actions of voltage regulation devices – but they are always kept within the statutory limits. Figure 1 (top) illustrates this variability and also that the supplied voltage can be higher than the nominal value (up to 18V in this case). This common practice in most countries ensures that remote customer voltages are above the lower limit (according to national standards) during peak hours.

Considering the acceptable range of operating voltages of modern appliances and the positive correlation between voltage and demand, reducing the supplied voltage of a house (within statutory limits) reduces the demand of appliances without any detrimental effect and, ultimately, without directly involving the customer. This raises the questions investigated by CLASS: What if the same principle is applied to millions of houses? Would the resulting demand reduction be meaningful for the provision of flexibility to the TSO?

A key aspect for the success of the CLASS voltage-led LM scheme is the ability to induce a voltage reduction throughout a *chosen* short period and to a *large number* of customers so as to achieve the desired demand reduction (period and volume of reduction eventually to be defined by the needs of the TSO). This idea, although promising, requires understanding how it can be deployed in a practical manner, i.e., leveraging the existing infrastructure as discussed in the next section.

2. Implementing CLASS: The Infrastructure of Today for the Flexibility of Tomorrow

DNOs around the world use a variety of devices to continuously maintain voltages within statutory limits. CLASS leverages this existing infrastructure, in particular the on-load tap changer (OLTC) of primary substation transformers - a common network asset in the UK as well as in many countries around the world. The OLTC, in normal operation, changes the transformer tap ratio in order to regulate the busbar voltage and, as a consequence, the voltage of all downstream customers. In European-style networks this is also the closest voltage control point to customers.

Figure 2 presents an overview of how the primary substation OLTC operates within the voltage-led LM scheme adopted in CLASS when flexibility is needed. This is also summarized in the five following steps:

1. The TSO sends a control signal to specific primary substations, which triggers the aggregated demand reduction needed at the required time window. This is possible as the DNO shares (via an ICCP link) real-time demand response tables that provide, for a corresponding group of primary substations, the time-varying capability in terms of voltage and, consequently, of demand reduction.
2. Based on the status of the distribution network (normal or abnormal operation), the DNO decides whether or not to allow the TSO to control the assets.
3. The TSO control signal then reaches the selected primary substations to change the OLTC tap position and, consequently, trigger the required voltage reduction.
4. This voltage reduction will consequently trigger a demand reduction in many of the appliances of all downstream customers.
5. The demand reduction from the selected primary substations, each feeding hundreds of thousands of appliances, will result in an aggregated demand reduction at the transmission-distribution interface, which is expected to satisfy the request of the TSO.

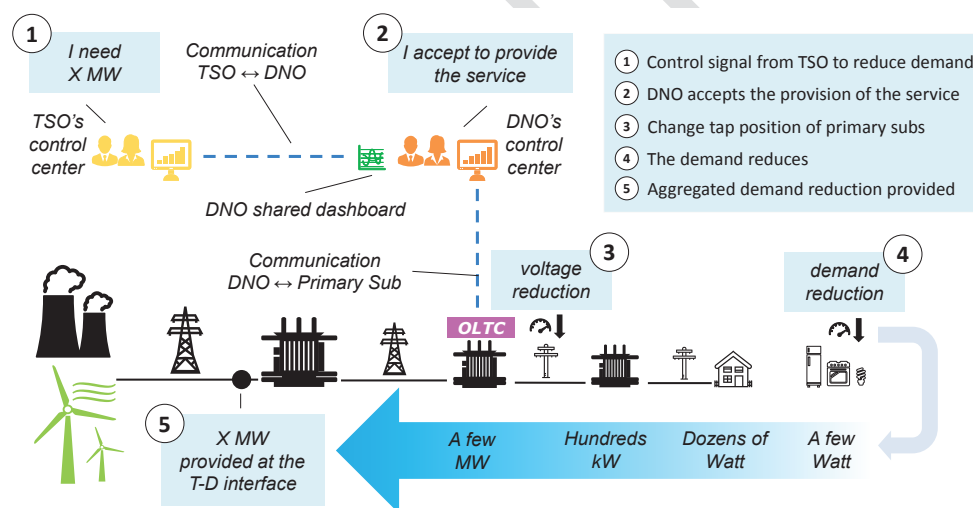


Figure 2 Illustrative example - CLASS application

The above process requires communication infrastructure to send signals from the TSO to the DNO as well as from the DNO to the OLTCs at primary substations (illustrated in Figure 2 with dashed lines). In addition, the OLTCs need to translate these signals into control actions. The voltage-led LM scheme proposed in CLASS achieved this in a practical way by leveraging the existing infrastructure as described in the next sections.

2.1. Existing Infrastructure

The voltage-led LM scheme proposed in CLASS requires communication infrastructure and remote control capabilities (see Figure 3). Fortunately, such capabilities, although to different extents, are part of existing distribution networks. The following assets can be found in the UK:

- **Voice-Frequency (VF) line.** This is the communication infrastructure that allows the exchange of digital and analogue data between the DNO control center and any primary substation. This is realized via serial 4 wire VF lines running at 9.6 kbps using Distributed Network Protocol (DNP3) and Teleconnect II protocols with an overall communications latency of approximately 9 seconds. This is part of modern Supervisory Control and Data Acquisition (SCADA) functionalities introduced to facilitate real-time visibility (active and reactive power measurements) of key infrastructure.
- **Remote Terminal Unit (RTU).** The RTU provides the interface between the primary substation and the DNO control center.
- **Automatic Voltage Control (AVC) Relay.** A relay that operates the OLTC based on local measurements and a predefined logic so as to maintain voltages of a specific point in the network (e.g., busbar) within predefined limits.
- **On-Load Tap Changer (OLTC).** The OLTCs (picture shown in Figure 4-a) are installed in primary substation transformers and are responsible for changing the transformer tap position during load conditions.

Although the above described network infrastructure was used in CLASS, some enhancements were required to add extra capabilities. This is discussed in the next section.

2.2. Enhancing Existing Network Infrastructure

In order to allow the successful deployment of CLASS, the communication infrastructure should be able to carry control signals from the TSO to each OLTC. In addition, the OLTC should be able to translate these control signals by changing its tap position accordingly (see Figure 3). For this purpose, the capabilities of the existing infrastructure were enhanced as follows:

- **Inter Control Centre Protocol (ICCP) link.** ICCP is a protocol that provides a mechanism for real-time data exchange typically used to exchange only data between TSO and DNO control rooms/centers. For the first time in the UK, an ICCP was designed and built to provide the TSO with *control* functionalities over the distribution network assets (OLTCs), which are essential for the eventual wide-scale implementation of a voltage-led LM scheme.
- **Autonomous Substation Controller (ASC).** This device, shown in Figure 4-d, translates the control signals produced by the TSO (delivered via the ICCP link and VF lines) or DNO into signals that the AVC can use to trigger the required tap changes in the OLTC. The ASC is the key device required in any of the primary substations participating in the voltage-led LM scheme proposed in CLASS.
- **Update or replacement of AVC relay.** Old AVCs are not capable of receiving signals from the ASC and therefore need to be replaced with modern units (Figure 4-d). In some cases, it was possible to adopt a less expensive solution in which a third component, called an Argus 8 relay, was used as the interface between the ASC and an old AVC.
- **Transducers and Data Transmitter (DT).** New transducers (Figure 4-b) were deployed at all 60 primary substations in the trial area to allow the corresponding monitors to provide higher resolution measurements. Then, a data transmitter given by the Nortech Envoy storage and 3G converter unit, shown in Figure 4-c, channeled these measurements (adopting a RS485 output) to a cloud-based storage to be used for further analysis.

- **Remote Customer Monitors.** Voltage monitors, installed at the remote ends of low voltage distribution feeders, verified whether the voltages of the furthest customers were below statutory limits during the deployment of CLASS.

The implemented updates of the existing infrastructure were found to be 57 times faster and approximately 12 times cheaper than traditional reinforcements otherwise required to incorporate the same capabilities.

3. Unlocking the Potential: Assessing the Benefits of CLASS

To quantify the potential volumes of demand reduction that could be provided by the CLASS voltage-led LM scheme, it is first necessary to assess the time-varying load models and voltage capabilities (defined below) for each primary substation involved in the trial. This is illustrated in Figure 5.

- **Load model.** This is the time-varying voltage-demand relationship that in the case of primary substations is given by the aggregation of hundreds of thousands of appliances.
- **Voltage capability.** This is the time-varying extent to which voltages can be reduced. The interactions across the whole distribution network (upstream and downstream the primary substation) must be taken into account to produce an adequate demand reduction quantification.

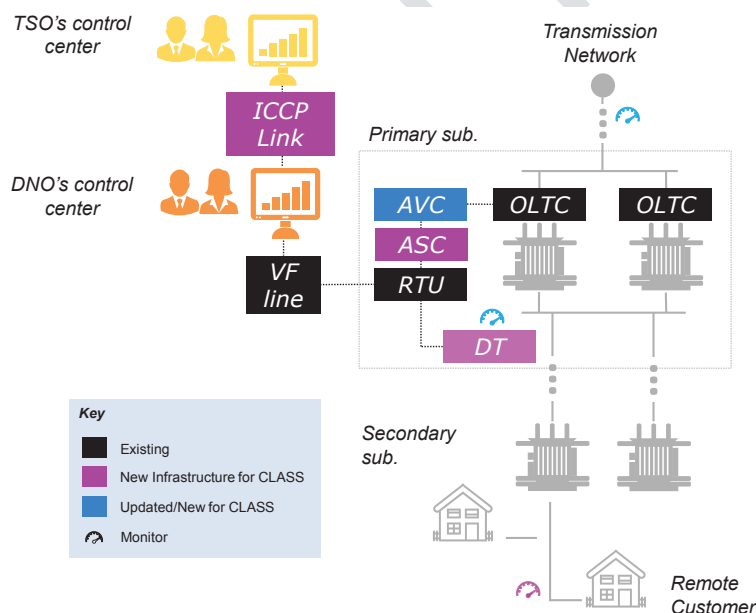


Figure 3 Overview of the communication, measurement and control infrastructure existing and required by CLASS

Two different approaches were used to determine realistic load models: measurement-based and component-based. The former used measurements from the CLASS trial in which both parallel primary transformers were tapped by several positions and the corresponding demand variation was measured. The component-based approach, on the other hand, estimates the load model using a bottom-up approach that aggregates demand and load models of downstream from customers without the need of measurements.

To assess the voltage capability of each primary substation, the three main voltage levels in the UK – extra high voltage, EHV (132 to 33 kV), high voltage, HV (11/6.6 kV) and low voltage, LV (0.4 kV) – were considered separately. Finally, once the time-varying load model and voltage capability are determined, the potential demand reduction can be quantified.

3.1. Realistic Load Models

The component-based approach produces an aggregated demand profile and time-varying load model by considering load models and demand profiles of single residential appliances fed by a given primary substation (Figure 6-a). Figure 6-b and Figure 6-c illustrate this for a mainly residential primary substation with more than 14,000 customers during a winter weekday. The np factor shown in Figure 6-c describes the primary substation load model by defining the exponential relationship between voltage and demand; the higher the np the higher dependency of demand to voltages. For instance if $np=2$ the demand will vary quadratically with the voltage; $np=1$ implies that the demand varies linearly with the voltage.

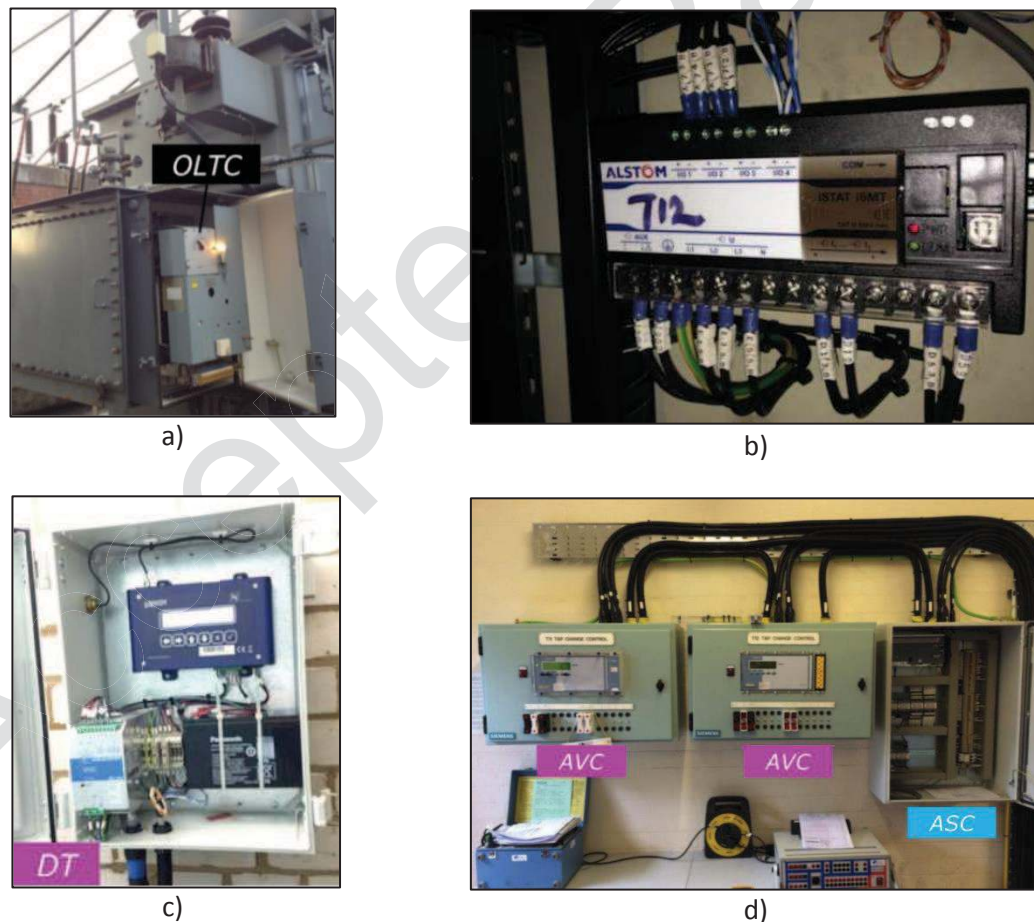


Figure 4 Primary substation equipment: a) On-Load Tap Changer (OLTC) b) Voltage and current transducer c) Data transmitter (DT) d) Automatic Voltage Controller (AVC) and Autonomous Substation Controller (ASC) (Source: ENWL, used with permission)

Thanks to a tool that simulates UK residential demand (per appliance) and load models for individual appliances available in the literature, the only information required for each primary substation is the number of residential customers and the total peak demand.

Despite the fact that the component-based approach is limited to residential customers and depends on other models, it manages to realistically capture the aggregated variability in the demand composition. As shown in Figure 6-b, during early hours of the day appliances that cool and heat, such as space heating (only ~20% of residential customers), are dominant. At peak time (6-7 pm) lighting appliances are the largest component. This, in turn, enables the component-based approach to estimate the aggregated time-varying load model (shown in Figure 6-c) without the need of actual measurements, thus making it possible to assess any substation where the number of residential customers and peak demand are known.

The measurement-based load model was developed for each of the 60 primary substations using data from field trials carried out within CLASS throughout a year. In these trials, both parallel transformers were tapped (on specific days and at specific times) one to three positions so as to reduce voltages by approximately 1.5 to 5%. The new tap position was held for 15 minutes to capture the corresponding voltage and demand changes. The noise and error in the measurements were then removed using a filtering process. Finally, using a load model formulation (chosen based on its practicality and the resolution of the available data), a curve fitting technique determined the parameters that best matched the measurements.

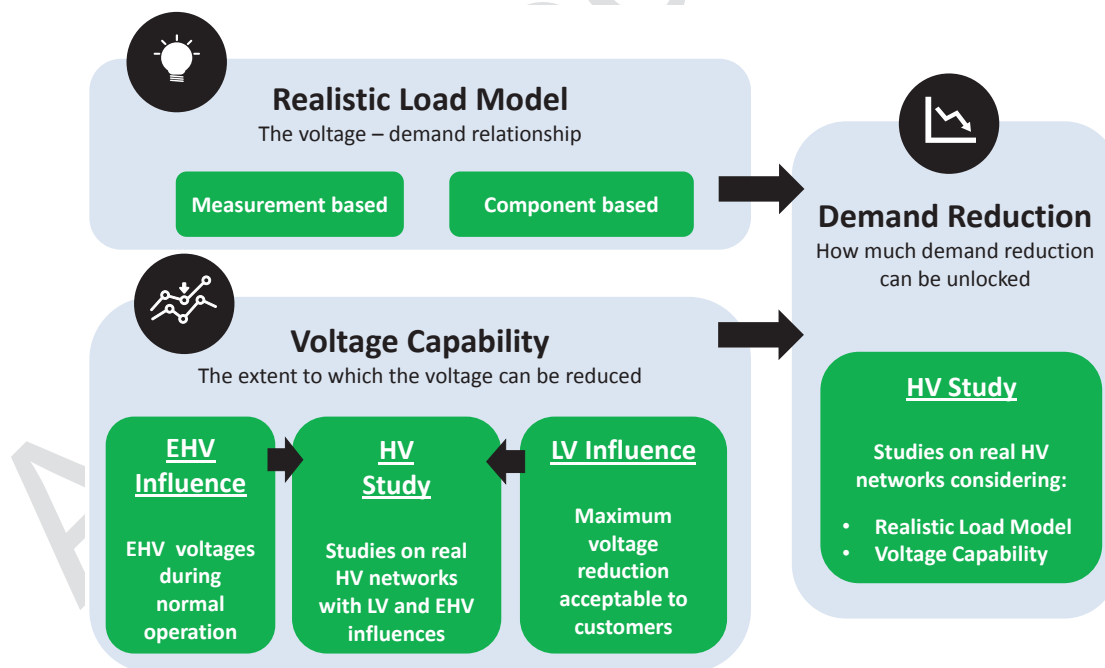


Figure 5 Methodology overview to quantify the demand reduction of a given primary substation

Given that different load compositions have different responses to voltage changes, the primary substations were also categorized into mainly residential, non-residential, and mixed based on their expected demand share at peak time. The resulting time-varying load models of primary

substations within the same category were found to be, in general, similar. In addition, due to the averaging process adopted to obtain these results, the intra-day variability within a season (Figure 7, winter) is smaller than the one found for a single primary substation (Figure 6-c, mainly residential). Nonetheless, throughout the year there are significant variations: np values that fluctuate from 0.67 (autumn) to 2.11 (summer) for mainly residential; from 0.86 (winter) to 1.98 (autumn) for mainly non-residential; from 0.7 (winter/summer/autumn) to 1.91 (winter) for mixed. More details and discussions of the results are available in the CLASS final report.

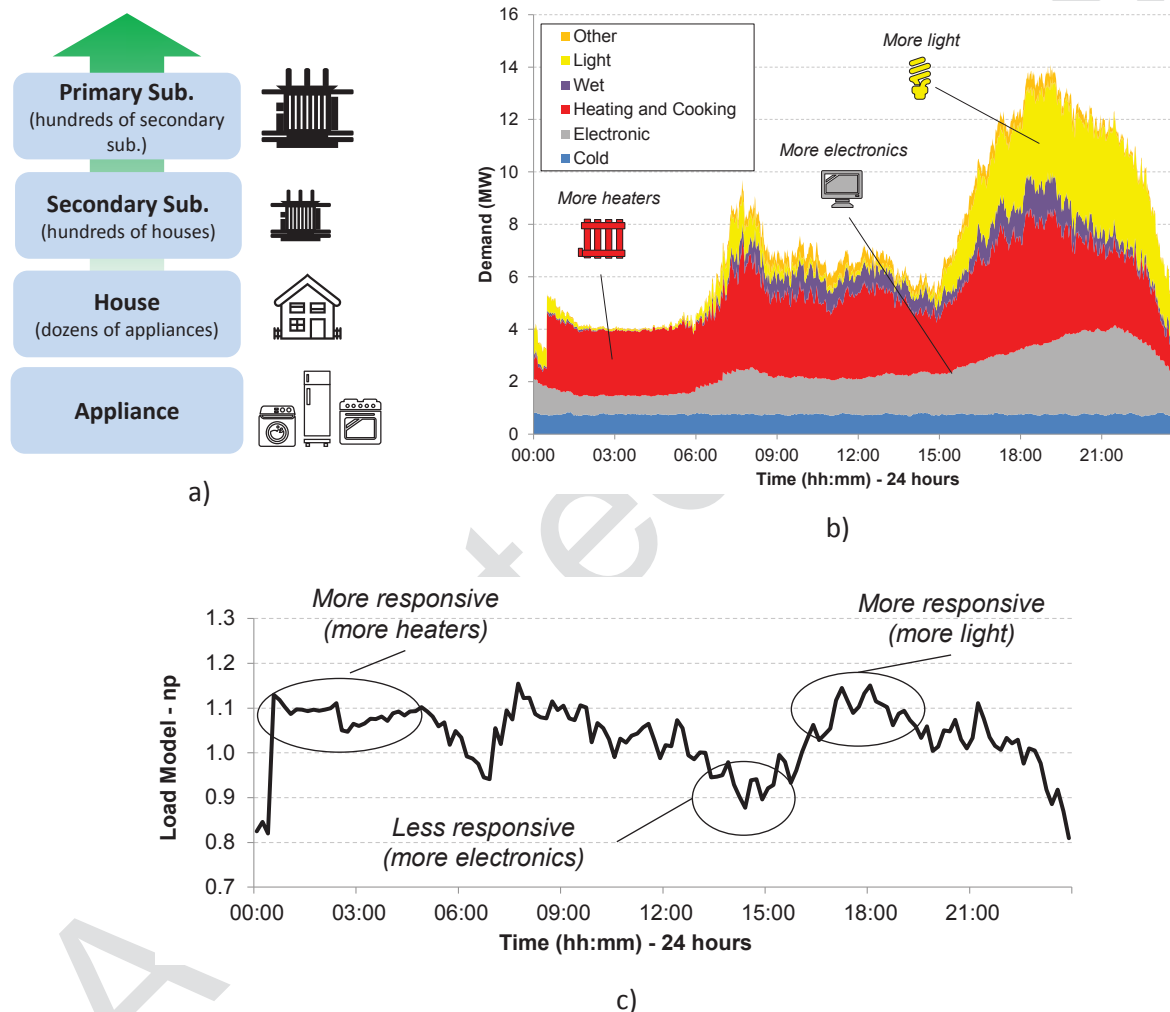


Figure 6 a) Overview of the component-based approach, b) Estimated primary substation demand with breakdown per appliance type, c) Estimated time-varying load model for the same primary substation

The values provided by the component and measurement based load models were relatively close when considering mainly-residential primary substations. Given that the component-based approach only considered residential demand (for simplicity due to the challenging task of modelling commercial and industrial demand), this provided a degree of validation. However, the larger discrepancies found with the other two categories of primary substations highlighted the contribution of non-residential demand. To account for these discrepancies, the component-

based load model was enhanced by embedding the measurement-based model for non-residential substations, thus creating a more flexible and reliable load model applicable to any substation without the need for extra measurements.

3.2. Voltage Capability

The extent to which the voltage at a primary substation can be reduced (i.e. voltage capability) is limited by downstream LV customers, whose voltages cannot be below statutory limits, and affected by upstream networks. For this purpose, a three stage approach quantifies the voltage capability taking into account these influences by considering simultaneously EHV and LV networks (also summarized in Figure 5) as described below.

- EHV Influence.** Voltages in EHV networks affect the tap position of primary substations which, in turn, dictates the number of available tap positions. For this purpose, a real EHV network model was used to estimate voltages at the primary side of primary substation transformers (blue square in Figure 8) and, ultimately, the corresponding OLTC tap headroom.
- LV Influence.** Ensuring that voltages of LV customers are above the lower statutory limit will determine the extent to which voltages at primary substations can be reduced. For this purpose, a set of 57 real LV feeders were analyzed using a Monte Carlo approach in which the lowest LV busbar voltage (green square in Figure 8) that does not affect customers is statistically quantified considering the variability in the residential demand profiles. This allows analysts to realistically quantify the impact that different LV busbar voltages can have on customers, essential for the voltage capability quantification.
- HV Study.** Lastly, considering the EHV and LV influences as well as the time-varying load models and demand profiles developed previously, a power flow analysis is carried out on the HV network associated to the primary substation so as to ultimately quantify the corresponding voltage capability and potential demand reduction.

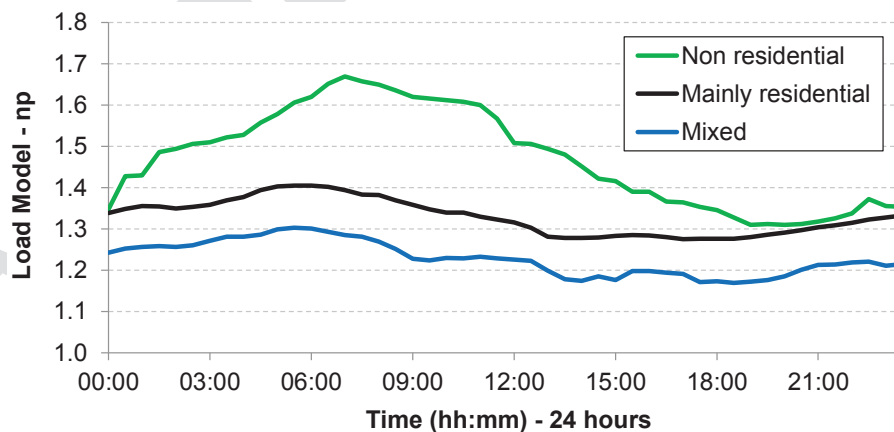


Figure 7 Field trial results: average time-varying load model per substation type (winter)

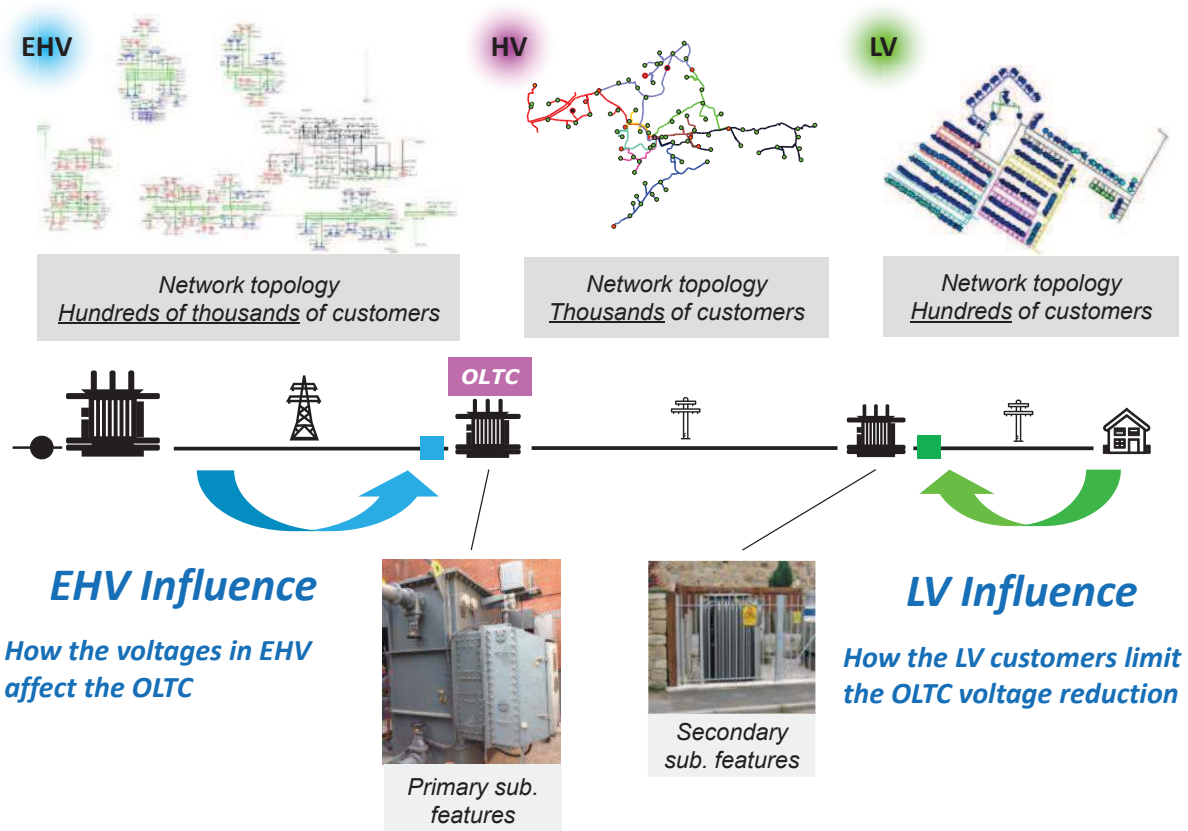


Figure 8 Voltage capability quantification in a whole distribution network

The volume of demand reduction that can be achieved at a given primary substation is therefore dependent on several factors such as demand composition and interactions across voltage levels, making it variable throughout the day and seasons. For instance, a mainly residential primary substation with a peak demand of approximately 15 MW (winter, at around 6 pm) was found to be able to achieve up to 600 kW of demand reduction (autumn, at around 6 pm) without affecting LV customers and considering all distribution network interactions. However, during times with lower demand and limited voltage capability this reduction could be as little as 40 kW (summer, early morning).

3.3. Regional and National Benefits

The benefits that could be unlocked by a load management scheme can be truly understood only when the contributions of millions of customers are considered. To this end, a quantification assessed the benefits that CLASS could unlock at both regional (for the North West of England with ~2.1 million residential customers) and national levels (for the UK with ~27.9 million residential customers). This was done by extrapolating the results obtained for the primary substations involved in the trials according to demand composition estimates for the regional and national cases.

The results of such extrapolations are shown in Figure 9 (seasonal half-hourly demand reduction). For the North West of England, with more than 360 primary substations and a peak demand of 4 GW during winter, it is possible to unlock a demand reduction that varies from 65 MW (summer)

up to 235 MW (winter). The North West of England represents about 1/15th of the total UK demand, which has circa 55 GW of peak demand (winter) and 27 GW of minimum demand (summer). It was estimated that a nationwide deployment of CLASS, assuming the same network operability as in the North West of England, could provide a demand reduction that varies from 1.1 GW (summer) to over 3.2 GW (winter).

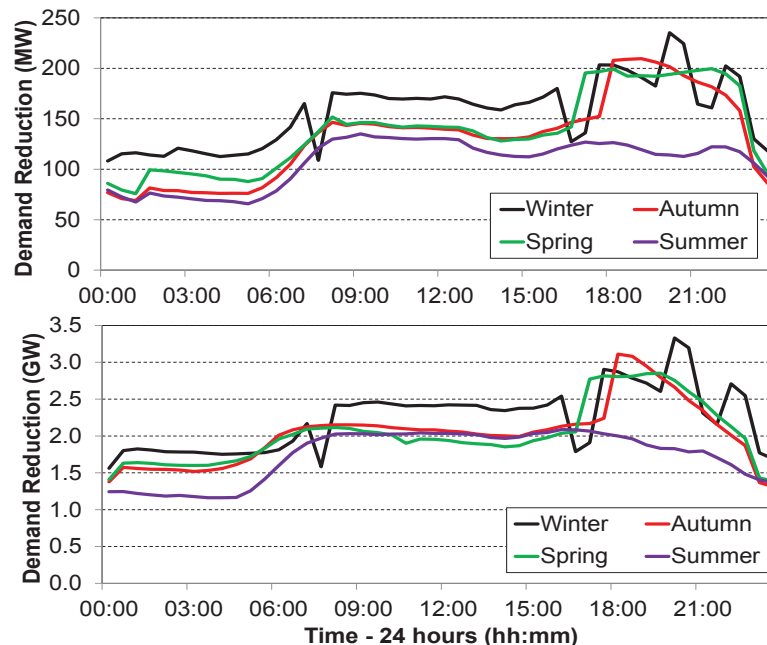


Figure 9 Large scale benefits of CLASS at regional (top) and national (bottom) level

Based on the above, initial estimates (see Figure 10) suggest that, between 2015 and 2029, the regional implementation of CLASS could reduce the cost of balancing services in the UK by approximately US\$ 244m, with customers receiving between US\$ 74m and US\$ 223m through reductions in their bills, depending on how CLASS is priced. If CLASS were to be gradually deployed nationwide between 2016 and 2041, it could potentially save up to US\$ 570m in balancing services cost, of which US\$ 156-543m could accrue to customers. It is worth noting that the benefits do not scale linearly with the expansion of CLASS from regional to national scale. This is because in such analysis it is assumed that, even without CLASS, the cost of balancing services decreases over time due to a growing adoption of technologies (such as batteries) and commercial arrangements to provide alternative sources of balancing services.

From the environmental perspective, it was found that the regional implementation of CLASS could avoid the emissions of up to 5215 tons of CO₂ equivalent (tCO₂e) per annum whilst the nationwide deployment could save up to 57366 tCO₂e per annum when compared to classical solutions such as fast-acting power plants.

Finally, a robust customer survey, based on more than 1,000 interviews and significant customer engagement via factsheets, leaflets, and video material has demonstrated that CLASS is also indiscernible to customers. Indeed, the proportion of customers who noticed a change in the

power quality of their supplied voltage during the CLASS trials was lower (3%) than the one during the baseline survey (4 to 5%) conducted before the trials.

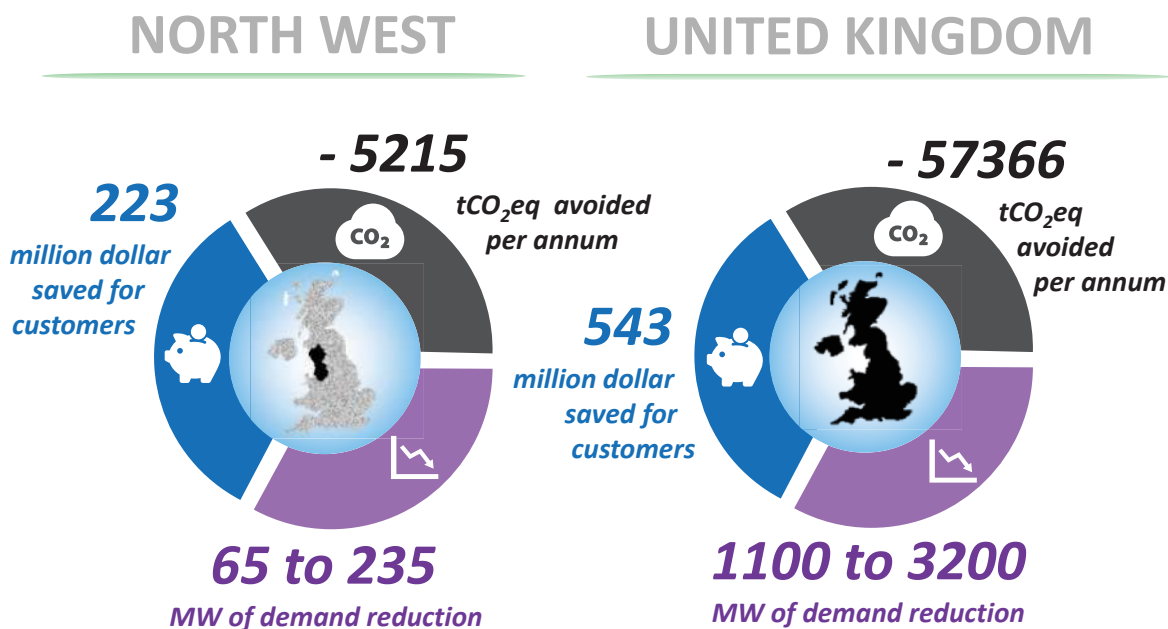


Figure 10 Benefits of CLASS in case of a regional (left) and national (right) deployment

4. Towards Business as Usual

CLASS demonstrated that it is possible to unlock the hidden potential of distribution networks by introducing an innovative, scalable and practical load management scheme that, for the first time, empowers DNOs to provide significant balancing services to the TSO.

CLASS has shown that there is an untapped potential in UK distribution networks of up to 3.2 GW of demand reduction, the equivalent of two combined cycle gas turbine power stations. This was found to have the capability to reduce carbon emissions by up to 57,366 tCO₂e per annum and deliver up to US\$ 543 million of savings for customers. In addition, the capability to leverage the existing communication and control infrastructure demonstrated the practicality and scalability of this approach, which cost-effectively involves millions of customers without having any negative impact on the perceived quality of supply.

However, the major challenge that prevents this Smart Grid solution from becoming standard practice for DNOs goes beyond any technical and economic aspect. Indeed, the main barrier is the lack of regulation allowing DNOs to participate in balancing services markets. Two possible solutions could be pursued:

- create a balancing market specifically designed for DNOs; or,
- require the DNOs to provide such balancing service with a separate compensation mechanism (not in a market) based on the CAPEX and OPEX required by the deployment of CLASS.

Ultimately, DNOs need to (and be allowed to) embrace a more active and flexible role by controlling their networks and evolving towards distribution *system* operators (DSOs) which actively manage their circuits, using CLASS and other methods.

CLASS is driving this transition, as clearly demonstrated by the UK regulator for Gas and Electricity Markets (Ofgem), which decided to extend the CLASS project in order to assess the possible economic benefits of nationwide deployment. This represents the first step towards a discussion needed to define new regulatory and market frameworks where DNOs can manage and operate their networks jointly with TSOs to address common challenges.

This project also incentivized closer collaboration between TSOs and future DNOs by pushing for a novel whole-system planning and operation of the power system (e.g., ICCP link that allows TSOs to access data from and control the assets of a DNO). This will not only accelerate the deployment of smart grid solutions, but will also encourage the holistic and cost-effective design and management of future power systems.

CLASS played a pioneering role in challenging the way in which DNOs manage and operate their networks by encouraging a more flexible and active role, which is essential to cope with the challenges of operating low carbon power system.

Although not discussed in this article, the CLASS project also investigated other potential solutions to defer investment and help manage the distribution and transmission networks. Demand reduction at peak time can also be used to release network capacity and hence avoid or defer substation upgrades (primary or upstream). CLASS can also be applied to temporarily increase customer demand and provide flexibility that avoids curtailing excess (renewable) generation. Although controversial, this could prove to be a sustainable solution in a market that allows such a scheme. CLASS also demonstrated two other interesting techniques. One is the possibility to trigger a much faster (seconds) demand reduction by tripping the circuit breakers of one of the pair of transformers (parallel transformers are common in UK primary substations) based on frequency measurements. The other is the provision of reactive power services to the TSO via tap staggering (applicable to parallel transformers) so as to counteract the effects on voltages from renewables and/or low levels of demand. These and similar DNO-based solutions ultimately highlight the significant potential that joint efforts between distribution and transmission can have for the cost-effective operation of future low carbon power systems.

5. For Further Reading

- *Customer Load Active System Services (CLASS) Project*. Available: <http://www.enwl.co.uk/class>
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6. Biographies

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