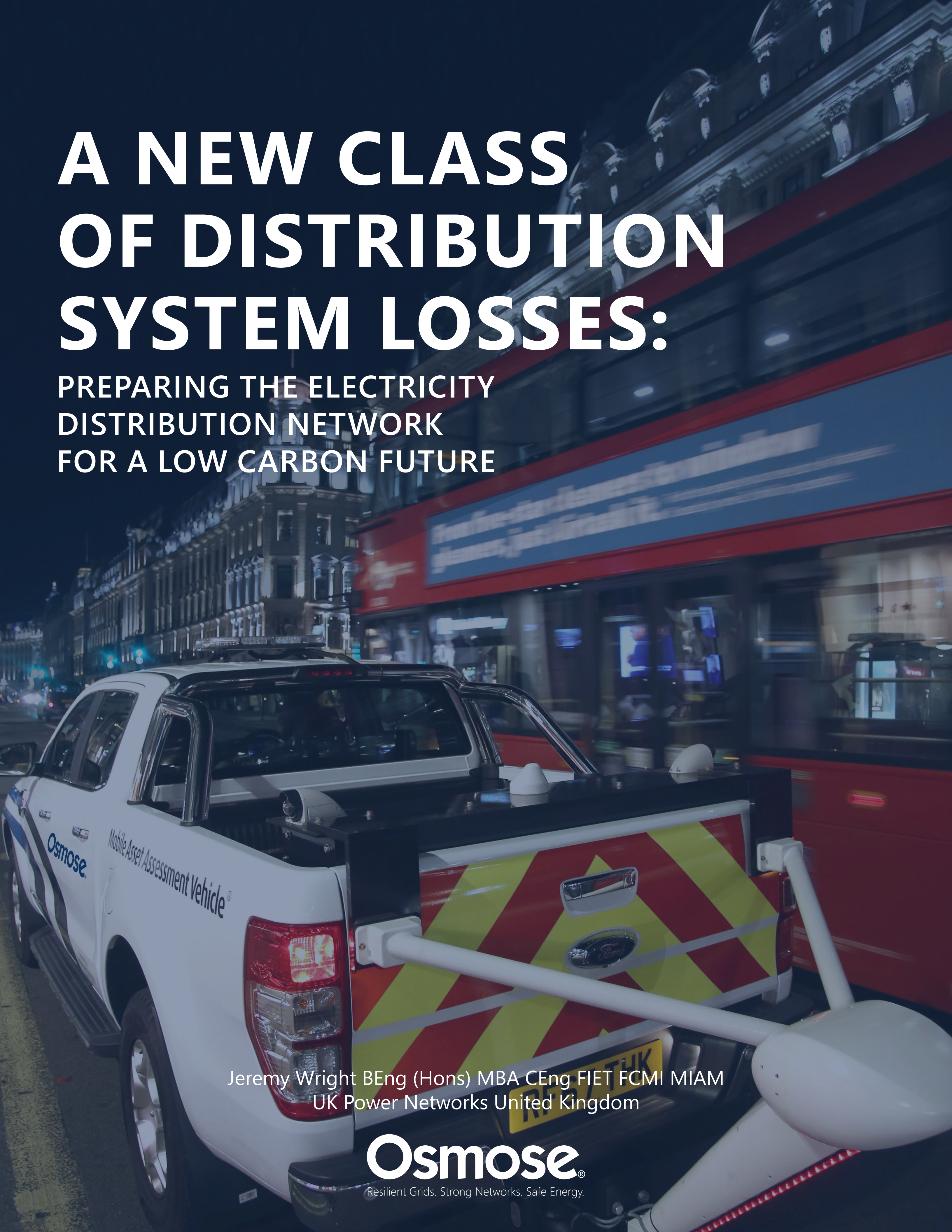

A NEW CLASS OF DISTRIBUTION SYSTEM LOSSES:

PREPARING THE ELECTRICITY DISTRIBUTION NETWORK FOR A LOW CARBON FUTURE

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In 1878, the age of electrification began in the United Kingdom with the installation of the first electric arc lamps in Central London.

Engineers quickly set out to design systems and equipment to deliver electricity to every building in London, just five years later Parliament enacted the first regulations on electric supply systems, and in 1891, Sebastian Ziani de Ferranti opened The London Electric Supply Corporation and the first AC Generating Station in London. The electric system that Sebastian Ziani de Ferranti envisioned was essentially a one-way system, where electricity from large generating stations, transmitted at high voltages and ultimately stepped down to lower voltages for use by customers. The electricity distribution system was designed to be highly reliable and ensure that power was delivered within narrow tolerance ranges for both voltage and frequency. Today, 140 years later, the electricity distribution system is evolving into an efficient, bi-directional system, allowing customer generated electricity to be sold back into the electricity distribution system.

UK Power Networks (UKPN) strives to develop innovative methods to manage the system and support the future grid. In 2016, UKPN initiated a research and development project to understand how contact voltage testing could be used to manage the low voltage (LV) electricity distribution network. The project involved using the Power Survey SVD-2000 platform to create the UK Power Network's Mobile Asset Assessment Vehicle (MAAV). The MAAV is an extremely sensitive electric field detection system integrated into a mobile platform. The MAAV is used to identify street level objects that have become energised because of underlying LV faults. These faults are known as contact voltage conditions.

Using this research, UKPN has identified a new class of No-Load losses on the LV electricity distribution system; **Contact Voltage Losses** account for the largest group of addressable losses on the electricity distribution system and are easily identified and mitigated. Unmitigated, these losses will have a significant impact on the efficiency of the grid in a low carbon future.

CONTACT VOLTAGE

When the insulation on LV secondary cable fails, conductive pathways are formed from the phase conductor(s) to the earth. Quite often these 'leaks' are high impedance faults. These type of faults draw relatively small amounts of current compared to the load capacity of the cables; since fuses do not operate, these faults can persist for long periods.

One significant characteristic of these LV faults is that they can energise street level objects. The voltages measured at the surface can range from just a few hundred millivolts to full system voltage. The energised objects may present a public safety hazard under certain conditions, but the energised objects also provide key evidence to finding the underlying faults that feed them. Anytime a street level object become energised, it emits an electric field signature that can be detected in the local vicinity. The MAAV is essentially a bespoke solution to the problem of finding faults from the low voltage electricity distribution system. The safety and system benefits from the MAAV were quickly evident during the initial UKPN trials. After just a few evenings of testing, several defects on the low voltage electricity network and public lighting system had been identified, allowing Engineers to quickly mitigate the defects before they affected customers.

STRAY VOLTAGE VS. CONTACT VOLTAGE

The Institute of Electrical and Electronic Engineers (IEEE) has defined these two voltage conditions. Stray voltage is the result of a normally operating electric distribution system, while contact voltage is the result in a defect (or fault) in either the phase conductor or neutral conductor of the electricity distribution network. The two terms are defined in IEEE-1695-2016 as follows:

> **Contact Voltage**: A voltage resulting from electrical faults that may be present between two conductive surfaces that can be simultaneously contacted by members of the general public or animals. Contact voltage can exist at levels that may be hazardous.
>
> **Stray Voltage**: A voltage resulting from the normal delivery or use of electricity that may be present between two conductive surfaces that can be simultaneously contacted by members of the general public or animals. Stray voltage is **not** related to electrical faults.

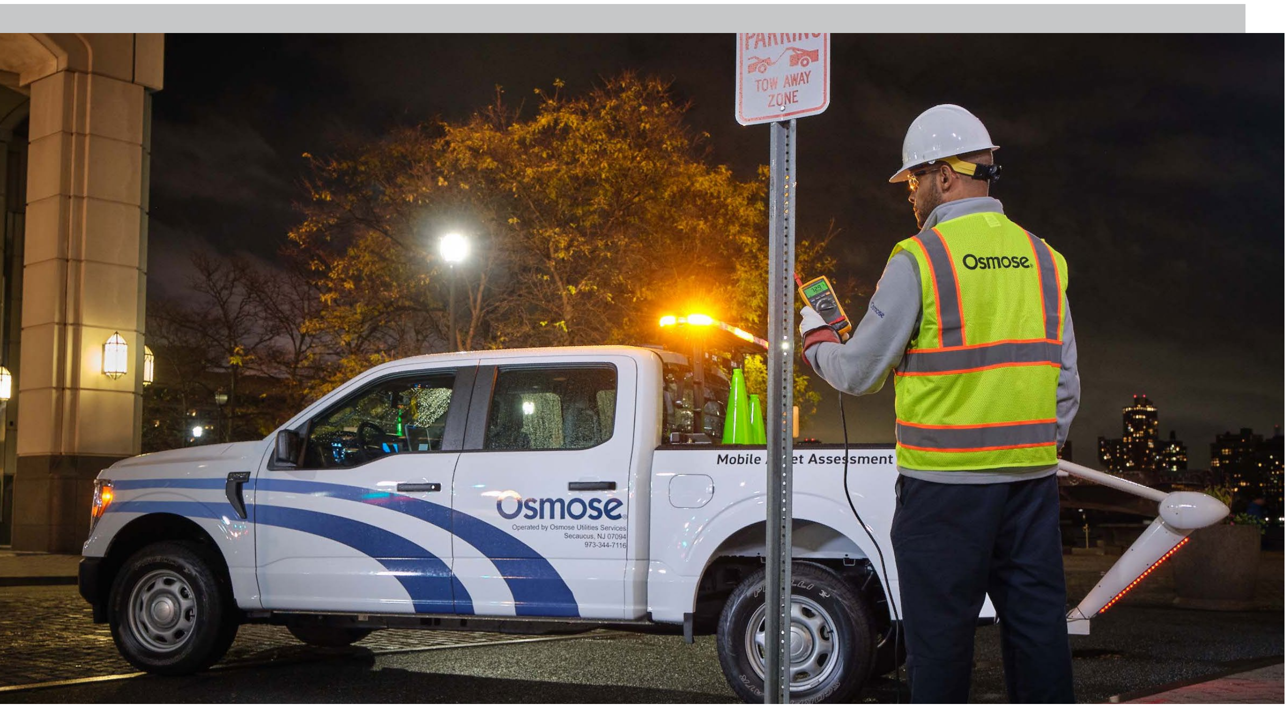
Stray voltage is most often discussed in the context of animal farms and swimming pools. These small voltages can cause shocks that cause animals not to eat, drink, or in the case of swimming pools, create discomfort for swimmers. It is impossible to determine if the voltage is a result of stray or contact voltage until an investigation has been performed and the utility can determine that no defects are present on the system.

AN INTERESTING OBSERVATION LEADS TO A SURPRISING DISCOVERY!

The first MAAV trial survey began in Central London in October 2016. The first survey found 155 energised objects over the course of the 425 mile survey. During an initial investigation of one of the MAAV findings, Jeremy Wright who was on site at the time noted that the defective three-phase lead sheathed LV cable was quite warm. Upon closer inspection of the LV cable, there were signs of long term heating to the paper insulation and some of the adjacent joints. The observation lead the research team to hypothesize that the heating was a result of the energy flow from the phase conductor onto the sheath of the LV cable. The sheath of the LV cable was in direct contact with the ground, allowing the current to flow into the earth.

With the LV cable nearly completely uncovered for the investigation, a current measurement was made, and the LV cable was found to be carrying 10 amps of current. The only load on the exposed cable was the fault to the earth. Whilst uncovering the LV cable certainly reduced the impedance to earth, using earthing calculations developed in the 1930's[1], the load from the contact voltage fault was calculated. The contact voltage fault current of an undisturbed cable was calculated to be 68 amps. The 16 kW resistive load provided a clear explanation for the damage and observed temperature elevation on the LV cable. What had been observed was the electrical equivalent of a leaking underground water or gas pipe.

Based on survey experience in cities around the world, faults on LV cables, public lighting systems and customer owned equipment are relatively common. The impact on total electrical system losses can be significant. In 2017, UKPN worked with researchers at Princeton University in Princeton, NJ, U.S.A. to prepare the world's first analysis of contact voltage losses but specifically for the *Analysis of Contact-Voltage Losses in Low-Voltage Electricity Distribution Systems of the U.K.*[2]



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[1] Dwight, H.B., "Calculation of Resistances to Ground," Electrical Engineering, 55(12): 1319 – 1328, Dec. 1936.

[2] https://www.ukpowernetworks.co.uk/losses/static/pdfs/analysis-of-contact-voltage-losses.f7e1d56.pdf

DISTRIBUTION SYSTEM LOSSES

In the U.K., the electricity system losses are about 7.7% of the total electricity generated. In 2016, that amounted to 26.3 TWh/yr of lost electricity. Analysis shows 7.4 TWh/yr are lost in the transmission of electricity at high voltage and the remainder is lost in the distribution system. Traditionally system losses are grouped into two categories, technical losses and non-technical losses.

Technical losses: Consumption that is required for the operation of the electricity system and includes losses due to the resistance of the conductors, operation of auxiliary loads and core losses in transformers.

Non-technical losses: Electricity which is delivered and consumed by customers but is not recorded. In the U.K., non-technical losses are estimated to account for 1 TWh/yr of losses.

Whilst the quantity of electrical energy lost from contact voltage LV faults is captured in the overall losses figures, it does not fit qualitatively into either of these two categories, since it is not required for the operation of the distribution system and customers do not consume the energy. Based on these facts, Jeremy Wright and the Project Team is proposing a new category called 'Contact Voltage Losses' be introduced and used to identify these specific type of losses.

Identifying this class of losses will enable electricity distribution utilities to actively search for the signatures associated with this unnecessary type of electrical consumption and quickly mitigate them. Mitigation not only reduces losses, it improves the safety and reliability of the system. By reducing the amount of electricity generated mitigation also reduces the amount of carbon dioxide emitted into the atmosphere.

CALCULATING THE LOSSES

There are a variety of physical defects that can result in contact voltage losses. For the purposes of estimating losses, contact voltage faults can be grouped into six general categories. LV cable phase faults and lighting column phase faults are responsible for most of the of contact voltage losses. The remaining four categories, faults on customer equipment, on both the phase and neutral side, along with neutral faults on public lighting and utility distribution systems, can be the source of contact voltage but are not significant contributors to losses.

- **LV Cable Phase Fault** – These are faults, which are located on underground LV cables. Losses from these faults are always unmetered losses. The losses from these faults are significant and can be modeled mathematically using formulas developed by H.B Dwight. Field observations have shown that the faults tend to energise the sheath of the cable or nearby underground objects.

  The loss can be modeled using the following equation:

$$R = \frac{\rho}{4\pi L}\left(\log_e \frac{16L^2}{as} - 2 + \frac{s}{2L} - \frac{s^2}{16L^2} + \frac{s^4}{512L^4} + \cdots\right)$$

Where: R = Resistance (Ω)
ρ = (Rho) Earth Resistivity (Varies with soil type) (Ω*cm)$^{-9}$
L = 2X Length of horizontal wire (in cm)
a = Radius of conductor (in cm)
S = 2X depth of conductor (in cm)

The average ρ value at the locations where voltage was found during the trial was 4,860 $(\Omega^{*}\mathrm{cm})^{-9}$ [3]. Using the formula and the following assumptions:

ρ = 4,860 $(\Omega^{*}\mathrm{CM})^{-9}$ Average
Soil Resistivity L = 2 Metres
of Energised Sheath[4]
a = 1 cm Sheath Radius[5]
S = 25 cm depth of conductor

The average earth impedance is 8.61 Ω with an instantaneous load of 26.7 amps or 6,144 watts. This is consistent with observations in the field.

- **Lighting Column Phase Fault** – These faults are similar to LV cable phase faults. When the phase conductor is inadvertently faulted to the earth, current flows into the earth, resulting in an unmetered loss. The analysis performed by H.B. Dwight also provides a formula to model the impedance of the lighting column to earth.

$$R = \frac{\rho}{2\pi L}\left(log_e \frac{4L}{a} - 1\right)$$

Where: R = Resistance (Ω)
ρ = (Rho) Earth Resistivity
(Varies with soil type) $(\Omega^{*}\mathrm{cm})^{-9}$
L = Depth (in cm)
a = Radius of conductor (in cm)

There are more than a dozen street light designs that are used in the Central London area, each with a corresponding diameter and depth. These values can be found in *Supplemental Standards for Traffic Signals and Street Lighting*[6]. The calculated average earth impedance for the listed lighting column designs is 10.93 Ω resulting in instantaneous load of 21.0 amps or 4,839 watts[7].

The calculated values for individual faults closely match fault values which have been measured in the field over the course of the research project in the Central London area. The soil composition and geology are significant factors in the losses from LV contact voltage faults. The researchers at Princeton University made estimates of fault impedances in other parts of the United Kingdom; on average a streetlight energised by a LV cable fault is responsible for 55.0 MWh/yr in losses, whilst an energised lighting column is responsible for an average of 46.1 MWh/yr in losses.

Estimating the total contact voltage loss for each of the Distribution Network Operators (DNO) is accomplished by combining data on the length of the LV cable installed in each DNO and the observed defect rate. Using this data, the researchers at Princeton were able to estimate the losses for each license area as well as for the whole of the UK. For the purposes of calculating the volume of energy lost, the faults are assumed to last for only a one-year period, although contact voltage faults have been observed to exist for significantly longer periods before they are mitigated through other traditional measures.

It is estimated that contact voltage losses are responsible for 0.6TWh/yr. of electrical losses in the U.K. Putting this value in perspective, it equates to the consumption of the entire U.K. on a typical Sunday.

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[3] Average value of British Geological Society Earth Resistivity Values for Lithography A and B at the 50% percentile at each location where an underground cable fault was known or suspected.

[4] Average of the length of energised sheaths found in surveys was 6.2 metres, 2.0 metres is used as a conservative estimate.

[5] Average measured diameter of cables found faulted in surveys

[6] City of London, “Supplemental Standards for Traffic Signal and Street Lighting,” STS 5.02, Nov. 3, 2017.

[7] Analysis of Contact-Voltage Losses in Low-Voltage Electricity Distribution Systems of the U.K, https://www.ukpowernetworks.co.uk/losses/static/pdfs/analysis-of-contact-voltage-losses.f7e1d56.pdf, Table 4

DNO	License Area	Average watts per CV	LV cable miles[a]	Annual CV detections	Avoided losses, MWh/yr
UKPN	Eastern Power Networks	1,110	42,064	3,875	37,693
	London Power Networks	1,961	23,912	2,203	37,833
	South Eastern Power Networks	1,868	28,304	2,607	42,500
ENW	Electricity North West	1,982	32,523	2,996	51,829
NP	Northern Powergrid (Northeast)	3,755	19,739	1,818	59,685
	Northern Powergrid (Yorkshire)	3,755	31,642	2,915	95,687
WPD	Western Power Distrib. (East Midlands)	3,755	37,342	3,440	112,912
	Western Power Distrib. (West Midlands)	664	30,536	2,813	16,170
	Western Power Distrib. (South West)	380	15,937	1,468	4,792
	Western Power Distrib. (South Wales)	1,982	12,127	1,117	19,325
SPEN	Scottish Power Energy Networks Distrib.	3,733	27,021	2,489	81,229
	Scottish Power Energy Networks Manweb	1,982	19,746	1,819	31,467
SSEPD	Scottish Hydro Electric Power Distrib.	664	not avail	not avail	not est.
	Southern Electric Power Distrib.	1,982	not avail	not avail	not. est.
Totals		**2,289**	**320,892**	**29,561**	**590,703**[b]
Total lost generation (assuming 4% loss from generator to DNO receipt)					615,315

(a) These are the effective miles of underground LV cables based on data calculated as described in the text. The mileages are for 2015/2016, except for UKPN, for which 2016/2017 data were available.

(b) Of this loss estimate, approximately 80% is unmetered (20% is on the customer side of the meter).

Figure 1 - Estimation of losses in the United Kingdom.
Source: Analysis of Contact-Voltage Losses in Low-Voltage Electricity Distribution Systems of the U.K., Larson, E. Chen, M., Princeton University 2018

Quantifying losses in the system is an important task as it aids in directing activities to reduce losses. The laws of physics dictate some of the energy consumed by the electricity distribution system, and reductions are not possible, these are labeled un-addressable losses; losses which can be eliminated are deemed addressable losses. In the case of addressable losses, it is important to identify the accessibility and relative level of mitigation effort required.

Contact voltage losses represent the largest category of addressable technical losses. DNOs in the U.K. had identified current and future losses reductions activities prior to the identification of contact voltage losses. These actions included traditional activities such as replacing old transformers, optimising conductor sizes and installing amorphous core transformers. Other potential future measures had also been identified but could not be cost justified presently. Putting this in perspective, mitigation of contact voltage losses represents an opportunity three times greater than that allowed by traditional methods. The Princeton study determined that contact voltage loss mitigation can be cost justified at current energy prices.

Category	MWh/yr
Contact Voltage Losses	615,315
Current Mitigation Programs (Excluding CV Losses)	86,116
Other Potential Future Methods	118,303

IMPACT OF CONTACT VOLTAGE LOSSES ON THE FUTURE ELECTRICITY GRID

The electricity distribution network of the future will probably look very different from the electricity distribution network that services customers today. In future, many customers will be largely self-sufficient and use a combination of on-site storage and generation to meet their electrical needs, with provisions to export excess capacity. Because of this transition, the electricity distribution network load will decline. Some types of losses, called load-dependant losses, will decline with the falling load; this includes conductor I2R losses and transformer load- dependant losses. Some Load-independent losses will also be reduced; for example, fewer transformers will be needed to meet the falling electrical demand, resulting in fewer load- independent losses from transformer cores.

Contact voltage losses however will remain constant and may even increase in fraction. Customers will continue to require a connection to the LV electricity distribution network in order to export power and for a supply of electric in the event of equipment failure and during peak periods, so the amount of LV cable is likely to remain constant. As discussed in the losses estimates the losses are a function of the number of installed miles of cable so the contact voltage losses will remain constant.

It is possible that contact voltage losses will increase with reduced reliance on the LV network. In the current distribution paradigm LV cable faults on the distribution network often impact customers, who in-turn notify their local network operator to make repairs. If these LV faults are un-noticed by customers, they could persist resulting in greater losses and may even influence the capacity of the LV system to accept exports from customers.

The constant level of contact voltage faults, coupled with a falling total system load will mean that system losses will increase as a percentage of power delivered. It is also likely that some form of fossil fuel derived electricity will remain a part of the generation mix for the near future, so any reductions in electrical load will still have the benefit of reducing the need for carbon intensive generation. Since contact voltage losses comprise a large singular component of the system losses, failure to proactively mitigate them will result in an increasingly inefficient distribution network in our low carbon future.