# Enhanced Understanding of Network Losses

## Literature review

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# Executive summary

Network losses are defined as the difference between the energy entering a distribution network, and the energy leaving it to serve customer needs. However, losses depend on the physical properties of the network, electricity demand, and the output of distributed generation at any given instant: calculating the losses of the whole network over a given period of time is, therefore, a challenging task.

This document reviews the state of the art in loss estimation and loss reduction in both academic literature and industrial practice. It discusses methods for resolving the variability of the demand; for estimating the impact of low-carbon technologies, including harmonic currents; the impact of load imbalance; methods for estimating the impedance of Low Voltage networks; and assessing the impact of measurement error and data granularity on the accuracy of loss estimation. This is combined with a review of the current regulatory and commercial arrangements for dealing with network losses within Great Britain (GB), and a review of the strategies being used to understand and manage network losses by the six Distribution Network Operators within GB.

The key findings are then summarised within four categories:

- **Impact of present and future network scenarios** including the variability of customer demand, present and future uptake of low-carbon technologies, estimation of phase imbalance and network characteristics; forecasting how the losses will be affected as demand changes and assets age.

- **Impact of Smart and non-Smart Technology** and how these can be used beneficially or how they can present new challenges. This includes the introduction of harmonic currents, and the impact of low-carbon technology on future demand. It also includes smart and conventional loss reduction techniques, varying from cable upgrades and phase rebalancing to soft open points, coordinated EV charging and vehicle to grid technology.

- **Impact of measurement errors,** which inevitably lead to lower accuracy in loss estimation. It is crucial to understand how the resulting uncertainty can be included within design, planning and operational decisions. Sensitivity analyses are proposed to increase understanding of how the measurement errors propagate through the system. This also includes the difference between the stated and actual impedance values of network assets.

- **Impact of monitoring at multiple aggregation levels** and how using data at different spatial and temporal resolutions impacts on the accuracy of loss estimation. The goal should be to find a compromise between the intensive process of using all available data, and a simpler method which cannot estimate losses with an acceptable level of accuracy.

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# 1 Definition of losses

## 1.1 Introduction

Electrical loss within the distribution system can be simply defined as the difference between the amount of energy entering the system and the amount of energy which reaches the network consumers [1]. Losses are an inherent by-product of the distribution of electricity and can be sub-divided into two main categories; technical and non-technical [1, 2]. Technical losses typically account for the greatest proportion of overall distribution system losses.

Increased losses indicate a higher level of network utilisation – which is a consequence of certain Smart technologies such as Real-Time Thermal Ratings. It is therefore not necessarily desirable to reduce losses in all cases, given that the increased losses could be as a result of deferring the construction of new assets. Another factor is the cost or carbon intensity of the energy – losses could be considered more problematic when the generation is more expensive and carbon intense, than when the generation is low cost and/or dominated by renewables – this can also be applied on the demand side, introducing the concept of whole system losses.

The overall complexity of the distribution network, in combination with insufficient metering at low voltage has meant that, to-date, accurate measurement of electrical losses has not been possible. This situation is likely to change as a result of the smart meter rollout in the UK.

This literature review provides a description of each of the main categories of electrical loss within the distribution system, a review of the methods developed for loss estimation, a review of Northern Powergrid's losses strategy with reference to strategies of other UK Distribution Network Operators (DNOs) and a review of the regulatory framework regarding losses within the UK.

## 1.2 Technical losses

Technical losses result from the physical properties of electricity distribution through the network [1], and can be sub-divided further to fixed losses, variable losses and unmetered supply as discussed in Section 3.2.2, Section 3.2.3 and Section 3.2.4 respectively [2].

### 1.2.1 Fixed losses

Fixed losses are the losses experienced when a network component is energised but without any real power flowing for servicing user energy needs. There are typically three main sources of fixed losses:

1. Corona discharge in overhead lines
2. Dielectric losses in underground cables
3. Losses from the energising of transformers, which are often referred to as 'no-load losses' or 'iron losses' [2].

Losses from dielectrics and corona discharge are typically far smaller than those observed in the energising of transformers, especially on Low Voltage (LV) distribution networks.

### 1.2.2 Variable losses

Variable losses occur as a result of power transfer through a network component for servicing user energy needs. The conductor heats up when carrying an electrical current due to its electrical resistance, and the loss is proportional to the current squared; [2] hence why variable losses are often referred to as $I^2R$ losses (or copper losses).

As conductor cross sectional area increases, resistance decreases, thus providing a reduction in losses for a given current flow. As a result of this characteristics a common method for loss reduction is the installation of a replacement conductor with an increased cross sectional area. The profile of the power transfer is also of significant importance when considering losses, as a highly variable load profile will result in significantly greater losses than one for which the same amount of energy is delivered at a lower constant power value.

### 1.2.3 Harmonics

Historically, the majority of loads connected to the distribution network had linear characteristics. However, there is now an increasing number of non-linear loads characterised by higher order current harmonics due to the wide-scale use of power electronic devices – which can range from fast-charging electric vehicles [1] through to LED lighting [2]. The voltage and current harmonics introduced by these devices, and those already present on the network, can lead to an increase in losses due to the additional current flows of higher harmonic order, with some studies finding this effect significant enough to alter the optimal configuration of the network substantially [3].

### 1.2.4 Load Imbalance

Load imbalance – in which the loading is not equally distributed across the three phases of the network – is common within distribution networks, especially at LV. As a result of the $I^2R$ relationship between current and losses, an unbalanced system will lead to greater losses than a balanced one for the same demand. Furthermore, if current flow in the neutral is explicitly modelled, this can lead to a further increase in losses arising from the imbalance [4, 5].

## 1.3 Non-technical losses

### 1.3.1 Introduction

Non-technical losses are sometimes referred to as commercial losses [1], and are the result of any system losses which cannot be directly attributed to the delivery of electricity through the system. Typically these losses are the result of measurement errors, or the theft of electricity from the network.

These losses can be sub-divided into unmetered supplies, energy theft and conveyance as discussed in Section 3.3.2, Section 3.3.3 and Section 3.3.4 respectively [2].

### 1.3.2 Unmetered supplies

Typical unmetered supplies within the distribution system are loads such as street lights, traffic lights and road signs. Each of these demands are estimated as opposed to metered.

Any energy consumed by auxiliary loads installed by the network operator to ensure safe and reliable network operation, such as substation heating and lighting, air compressors and cooling are also examples of unmetered supplies. One emerging factor for consideration in the development of the smart grid are parameters such as the heating and cooling of energy storage systems within primary or secondary substations.

A typical load profile is assumed for each of these demands at present. Where errors exist between the assumed and actual load profile, or inaccurate equipment inventories exist, then this will result in unmetered supplies and an under or over-estimation of losses [2].

### 1.3.3 Theft in Conveyance

The significant difference between unmetered supplies and theft in conveyance is the known presence of a meter. For unmetered supplies, records of loads are known and estimated due to the absence of available metering, theft in conveyance refers to the illegal removal of electricity from the system at a location where a meter is known to exist or as a result of an illegal, unregistered connection to the network.

These losses can also occur when usage is inaccurately recorded in the national electricity settlement system. Examples of conveyance losses include missing or unregistered metering points, incorrect metering point energisation and incorrect registration of metering systems [2].

### 1.3.4 Conveyance

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# 2 Loss estimation

## 2.1 Overview of Loss Estimation Methods

Losses can be estimated by measuring the power entering the system and the power leaving the system, and taking the difference. Any error in the measurement equipment would be reflected in the estimated losses.

An alternative method to estimating technical fixed and variable losses is through utilising a load flow calculation using many common power systems analysis software packages. A load flow calculation estimates the losses based on a snapshot of the load profile and the network impedances. If the operating temperature of the conductor increases from 0°C to 100°C, then its resistance increases by just over 40% [7]. The operating temperature depends on several factors including the time varying use of the network component, its thermal time constants, and the ambient temperature [8].

## 2.2 Impact of Measurement Errors

All measurements of network parameters have an associated measurement error – these errors will have an impact on calculated parameters, including network losses. A Network Innovation Allowance (NIA) project by Western Power Distribution (WPD) aims to quantify technical losses on the LV and HV network, and determine the minimum information required to accurately predict network losses [9]. The project will be completed in July 2018 and reports in October 2018. In an interim report [10], estimated losses were reported for the network load on a minutely resolution using two calculation methods:

- Power difference

- Current measurements and $I^2R$ calculations

The $I^2R$ method displayed a loss uncertainty on the HV feeder of ±0.06% of the delivered power or ±5% of the mean losses. On the LV feeder, the loss uncertainty of ±0.02% of the delivered power or ±10% of the mean losses. The $I^2R$ method assumes constant resistance and voltages within the network, and does not take into account unmetered supplies or potential energy theft (which accounts for an estimated 1% of energy distributed [7]). Consequently, the variability of losses using the power difference method was observed to be much greater than the variability in the estimate using $I^2R$.

The use of the $I^2R$ method requires the DNO to know the line impedance. In an HV or EHV network, this is likely to be well known, although this value will vary with the temperature of the asset and has the potential to change with the asset's condition as it ages. In LV networks, the impedance is more uncertain; methods exist for estimating these values, but they rely on a significant number of measurements within the network, and require a substantial amount of computation [11, 12] which would not be practical to undertake on every LV network.

The losses estimated by the power difference method can also be different to that used for billing purposes, due to conveyance losses. The potential error arising from the various movements due to inaccurate load profiles and actual meter readings replacing estimates over a sufficiently long period of time averages around 0.15% of the units distributed for most DNOs [7].

## 2.3 Impact of Demand Variability and Data Granularity

Lost estimation presents a number of challenges: because technical losses are non-linear, it is not appropriate to use an average value for the load. Instead, various approaches have been used to develop Loss Load Factors, Load Factors, or Equivalent hours (these are defined in Table 1), the purpose of which is to allow the use of a single value for the load on the network to calculate the total losses for a year [13]. The relationship between Loss Load Factor and Load Factor is explored by both [14] and [13] by considering two extreme cases, and thereby providing a credible range in which the relationship exists. This then enables estimation of the Loss Load Factor based on the Load Factor, allowing estimation of the losses within a range of ±10% of an estimate made using an observed Loss Load Factor. Further to this, the resolution of data used to calculate losses has a substantial impact on the accuracy of the calculation: research by Northern Powergrid and Sheffield university suggested that using half hourly data resulted in an under-estimate of between 24% and 9% compared with using one-minute data from smart meters [15].

| NPG Term | Definition |
|---|---|
| **Loss Load Factor** | The actual losses over a period, T, divided by the maximum observed losses within the period multiplied by T [14]. |
| **Equivalent Hours (Heq)** | The number of hours at maximum load which gives the same total energy loss as the actual system with the varying load [14] – can be calculated by T × Loss Load Factor |
| **Load Factor (LF)** | Ratio of the average load to the maximum load [14]. |

*Table 1: Definitions of commonly used terms in loss estimation*

Many authors have presented methods for breaking the demand down into peak, average, and minimum demand periods, and using a weighted sum of these to calculate the total energy loss [16]. However, in many cases the averaging method used for the periods is not appropriate, due to the non-linear relationship between load and losses, and therefore these methods will systematically underestimate network losses. The authors of [17] present a simplified approach to calculating line losses based on the Loss Load Factor of each feeder within a network and a weighting based on the proportion of the overall system energy transferred by each feeder. However, the method is not adequately validated – instead it is merely claimed that the answer provided is credible – and a limited sensitivity analysis is provided to show the influence of power factor on the result.

## 2.4 Impact of Low Carbon Technologies

As part of the low carbon transition, an increasing amount of heating and transportation load is expected to be served by electricity distribution network [18]. There is also already significant levels of generation present throughout the distribution network. All of these changes can materially impact distribution network losses through increased energy demand, changes in the load shape, and introduction of harmonic currents. The existing penetration levels have had a minimal impact on overall network losses, but studies suggest that LV network losses can increase in a quadratic form with the penetration of heat pumps [19] – although this can be mitigated through the use of more efficient heat pumps and better insulation – and that even with smart charging of EVs, off-peak losses could increase by as much as 40% with an EV penetration level of 60% [20].

Distributed generation – particularly variable renewables – can lead to an increase or decrease in losses, depending on the power output of the generator relative to the local demand, and how the generator and load vary with respect to time. How this variability is accounted for can also have a significant impact on the accuracy of any loss estimation technique [21].

In estimating the losses of future distribution systems, the ability to make informed forecasts about the likely uptake and usage of low-carbon technology – and how they will impact on the underlying energy demand – is therefore an essential requirement.

# 3 Regulatory handling of losses

Electricity entering or exiting the DNOs' networks is adjusted to take into account network losses. This adjustment is made to ensure that energy bought or sold by a User, from/to a Customer, accounts for energy lost as part of distributing energy to and from the Customer's premises. Electricity industry settlement systems charge suppliers for network losses and are therefore paid for by the customer [22].

## 3.1 Line Loss Factors

Losses on the Distribution Networks are allocated through the use of Line Loss Factors (LLFs) also referred to as Loss Adjustment Factors. Line Loss Factors are multipliers which are used to scale energy consumed or generated to account for losses on the UK's Distribution Networks. LLFs are applied in both Central Volume Allocation (CVA) and Supplier Volume Allocation (SVA) [23]. DNOs are responsible for calculating the LLFs and providing these factors to Elexon. Elexon manage the Balancing and Settlement Code. The Code covers the governance and rules for the balancing and settlement arrangements [24].

### 3.1.1 Calculation of Line Loss Factors (LLFs)

LLFs are calculated in accordance with BSC Procedure (BSCP) 128. BSCP 128 determines the principles which DNOs must comply with when calculating LLFs. Each DNO that does not mirror LLFs must submit a methodology for calculating LLFs that complies with the BSCP128 LLF Methodology Principles. This methodology statement is not subject to approval by the Authority, and is in addition to our Use of System Charging Methodology statement [25].

LLFs are either calculated using a generic method or a site specific method [25]. For the purposes of LLF calculation methodologies the customer voltage categories are defined as follows in[26] and [27]:

- Extra High Voltage (EHV): – Premises or distribution systems metered at voltages above 22 kilovolts (22kV); or – Premises or distribution systems metered at below 22 kilovolts (22kV) but connected to a dedicated primary substation with transformation ratios of 132/66/33kV to the metered voltage.
- High Voltage (HV) - premises or Distribution Systems metered at voltages of less than 22 Kilovolts (22kV), but greater than 1 kilovolt (1kV); and
- Low Voltage (LV) - premises or Distribution Systems metered at voltages of less than 1 kilovolt (1kV).

DNOs are obliged under Standard Licence Condition 14 of the Electricity Distribution Licence to publish a statement of charges and charging principles for the use of their distribution system. The form of the LC14 statement is approved by the Authority (Ofgem). The LC14 statement is required to contain a "Schedule of Line Loss Factors", which provides the LLFs which must be used to take account of losses on our distribution network. LLFs are also made available to Elexon (and therefore all market participants) by the DNOs through the provision of the dataflow, D0265 for SVA LLFs and an Elexon prescribed data format for CVA LLFs. All LLFs are calculated and submitted to an accuracy of 3 decimal places (BSCP128 Principle 2) and in accordance with the following Seasonal Time of Day (SToD) time periods (BSCP128 Principle 8); example SToD periods for Northern Powergrid (Northeast) are shown in Table 2.

| Time Periods – All times below stated in GMT | |
|---|---|
| Winter Peak | 1630–1830, Monday – Friday during the months of December, January and February |
| Winter Weekday | 0730–1630 & 1830-2000 Monday – Friday during the months of December, January and February<br>& 0730-2000, Monday – Friday during the month of November |
| Night | 0030 – 0730, Every night of the year |
| Other | Any other time not specified above |

*Table 2: Seasonal Time of Day (SToD) time periods*

The generic (or mass market) is used for sites connected at LV or HV and the site specific method is used for sites connected at EHV or where a request for site specific LLFs has been agreed. Generic LLFs will be applied to all new EHV sites until sufficient data is available for a site specific calculation. The Elexon website [23] contains more information on LLFs. This page also has links to BSCP 128 specific DNO LLF calculation methodologies. Generic LLFs are calculated using a methodology similar to that developed by EA Technology, in conjunction with the majority of distribution businesses. This methodology has been built into DNOs' "General System Losses models". This process produces averaged LLFs for use with all customers connected at LV and HV voltage levels, and temporarily for new customer sites connected at Extra High Voltage (EHV) until a site specific LLF is calculated.

Site Specific Loss Adjustment Factors are calculated for those sites connected at EHV; or where the DNO agrees to apply site specific calculation following a customer's particular request [26]. This is done using an electricity industry methodology employing specific load flow models developed for each individual site. The treatment of generation sites within these models is in accordance with industry guidance documents issued by the Settlement Subcommittee Operations (SSC (OP)). In particular the following documents, SSC (OP) 1390 (Revised), "Guidance Northern Powergrid (Northeast) Ltd Distribution Losses Methodology Page 1 of 8 note for the calculation of loss factors for embedded generators in settlement" (1992) and the sub group report MDC/54/1166 (1995) refer. These methodologies are described further in the following sections below.

### 3.1.2 Generic LLFs

Generic LLFs calculations are based in the same overall methodology for every DNO. Below is the methodology used by NPg and as recorded in [26]:

Generic LLFs are calculated for all categories of SVA registered sites for the predetermined SToD time periods of the year. The allocation methodology and software model, similar to that developed by EA Technology, is utilised to calculate the generic loss adjustment factors. The generic loss adjustment factors are recalculated and published at least every 2 years for the following 5 generic Line Loss Factor Classes (LLFC) groups:

- Extra high voltage (Default EHV class until a Site Specific LAF is calculated)
- High Voltage provided at the terminals of a substation with an incoming voltage of 132kV,66kV or 33kV (HVS)
- High Voltage provided from the network (HVN)
- Low voltage provided at the terminals of a HV/low voltage substation (LVS)
- Low voltage provided from the network (LVN)

In overall principle the model takes into account the units entering the system from known purchases at GSPs, embedded generation, etc and the units leaving the system, based upon known unit sales. The total system losses therefore take into account both technical and non technical losses and are given by the following expression.

Total System Losses = Units Entering System - Units Leaving System

Total system losses are generally referred to as Grid Supply Point Group (GSPG) losses

In detail the five voltage levels of 132kV, 66kV, 33kV, HV and LV and the six transformation levels of 132/66kV, 132/33kV, 132/HV, 66/HV, 33/HV and HV/LV are represented within a network model. 20kV, 11kV and 6kV are treated as HV for the purposes of this exercise. Other transformation ratios, such as those between 'HV' pressures or 33kV/LV are ignored on the grounds of proportionality for the purposes of this exercise. The model is populated with a set of standing data. For example, the fixed loss constant (in megawatts) and the variable loss constant (per megawatt) for each voltage and transformation level are contained within the standing data.

The model is also populated with the metered volumes of energy per annum at the various network voltages, including the energy metered profiles at the connection points with National

Grid Electricity Transmission and for site specific demand and generation. Common demand and generation profiles (net demand) are produced in relation to each HV & LV LLFC group. This data enables accurate LLFs to be calculated for the predetermined SToD time periods of the year.

A 'Top-Down' approach is used for estimating network losses starting from the 132kV (or other lower voltage where applicable) bar at GSPs. The energy delivered from the higher voltage level is used to deduce the losses on the assets and thus the energy passed through to the lower voltage level. At each voltage level, the losses already calculated and attributed to relevant customers via EHV site specific loss calculations are taken into account. The model is populated with aggregated data from all Site Specific SVA and CVA sites and weighted Site Specific LLFs at each voltage. The model then calculates the specific generic losses associated with these groups of site specific sites along with the losses for the other generic LLFC groups. The model calculates the power passed through the network into the next voltage level below using the following empirical equation:

$$\text{Pout} = \text{Pin} - \text{v Pin}^2 - \text{f} - \text{L}$$

where Pout = Power out of voltage level into lower voltage level, Pin = Power into voltage level from higher voltage level, f = Fixed loss constant for voltage level, v = Variable loss constant for voltage level, L = Metered sales at voltage level.

This is repeated through the voltage and transformation levels until the LV network is reached. The half-hourly metered load for that half-hour is then subtracted to leave the estimated demand for that half-hour attributed to the quarterly metered customers. This is not known for each individual half-hour. Therefore the total estimated quarterly metered demand for the year is compared with that used in producing the estimate of the Units Leaving System. There will always be a very small discrepancy in these two figures due to assumptions in the model and variations in LV metered data accuracy, e.g. time registration unmetered supplies, theft etc. This discrepancy represents unapportioned electrical losses and is thus reapportioned iteratively across all voltage levels by the model itself to match the two values. The model achieves this by adjusting the variable losses via the variable loss constants. Since estimates of fixed losses and of variable loss constants at EHV are more robust than the estimates of the variable loss constants at lower voltages the adjustments are weighted towards the variable loss constants at the lower voltages.

At this stage the model also apportions losses in the system at each voltage level to each electrical unit of energy flowing through that level. To calculate the loss adjustment factor for a predefined SToD period, the total system loss is weighted by the corresponding Loss Load Factor for that SToD period. A customer is thus allocated LLFs dependent upon their point of connection with the network in relation to the 5 generic LLFC groups identified. Import and Export supplies located at the same site and voltage level will be allocated to the same LLFC group and thus share the same values, so that generation receives the full benefit of offsetting demand.

### 3.1.3 Site Specific LLFs [26]

Site Specific LLFs are calculated for all CVA and EHV SVA registered authorised users on an individual basis: or where the DNO agrees to apply a site specific calculation following a customer's particular request. Each customer's supply is modelled individually using a model representation of the distribution network that contains details of the customer's load profile, the system load profile and the specific DNO assets used to supply them. They are recalculated when there has been a relevant change to the site or network, and at least every 5 years. The site specific LLF comprises a fixed loss element and a variable loss element. Losses are calculated for the four periods of the year similar to the system losses, taking into account real current flows and asset sharing, they therefore account for technical losses only. Significant changes year to year are much more likely to occur when losses are calculated on a site-specific basis. Changes in demand or consumption on one site can cause real changes to the losses the DNO incurs due to that particular customer's connection. Similarly, changes to power flows at adjoining sites can change the losses incurred by any given point demand (or generation). Such changes are not swamped by the overall inertia of the entire network and consequently site-specific losses are more volatile. Significant changes are, however, the exception rather than the rule as customers' overall demands and consumptions tend to remain fairly consistent (allowing for seasonal variations) given no major site or economic changes. Site specific LLFs are calculated for both load and generation customers.

The specific method for calculating Site Specific LLFs for every DNO is recorded in their Losses Methodology Statement.

## 3.2 RIIO-ED1 Reduction of Losses mechanisms and incentives [28]

Historically Ofgem incentivised DNOs to reduce losses against a target. In RIIO-ED1 Ofgem implemented a losses reduction mechanism consisting of four components: licence obligation, losses strategies, annual reporting and discretionary reward.

### 3.2.1 Licence obligation

Ofgem has an included an obligation in the DNOs' licence requiring them to design, build and operate their networks to ensure that losses are as low as reasonably practicable. This sits alongside the DNOs' overarching obligation to develop and maintain an efficient, co-ordinated and economical distribution system. These conditions are enforced in the same way as for any other breach of licence. Where a DNO has the right to recover the value of any electricity theft, the licence requires it to try to recover that value as long as the costs of doing so are not likely to exceed the sums recovered.

### 3.2.2 Losses strategies

Each DNO needed to develop a losses strategy. They must keep an up-to-date version on their website, identifying any changes from the previous version and the reasons for them. The strategy explains the DNO's overall approach to managing losses. It identifies specific projects or actions, with timescales, deliverables, costs and benefits. Actions should be justified with the associated benefits (e.g. carbon abatement) using a "whole life costing" approach and cost benefit analysis (CBA). Ofgem expects the DNOs' actions to consist of more than just complying with the EU eco design directive requiring the use of "low loss" transformers. DNOs' strategies should demonstrate they understand best practice, as well as how they propose share it across the industry. Ofgem plans to introduce a losses incentive for RIIO-ED2 and they expect the DNOs to include proposals for establishing a reliable losses baseline during RIIO-ED1. They should consider how power system modelling, innovative approaches, sharing of best practice and shared initiatives could help.

### 3.2.3 Annual Reporting

Ofgem requires DNOs to report annually on their activities to reduce losses during the year. This includes annual and cumulative improvements and actions planned for the following year, accompanied by cost benefit analysis.

### 3.2.4 Losses discretionary reward

RIIO-ED1 includes a discretionary reward for loss reduction activities. This is for actions in addition to those in the DNOs' strategies. Up to £8m will be awarded in 2016-17, £10m in 2018-19 and £14m in 2020-21. The DNOs receiving awards will be able to recover them in allowed revenues in the following year. The criteria for the awards are included in the Losses Discretionary Reward Guidance Document.

### 3.2.5 Electricity theft

Electricity theft is dealt with under various mechanisms, depending on the circumstances. Ofgem expects DNOs to at least maintain their current levels of support for suppliers in identifying and resolving theft. They should also take all reasonable cost-effective steps to resolve any cases of electricity theft from their distribution systems. The core elements of the approach are listed below:

- Where possible the link between the supplier and the customer should be maintained. DNOs are required to tackle theft where a supplier is not responsible.
- DNOs are required to act where someone makes an illegal connection, restores a disconnected supply, or where a supply has never been registered.
- Where DNOs have the right to recover the value of electricity taken, they must take reasonable steps to do so without incurring disproportionate costs. They must also seek to recover the associated costs and share any funds recovered with customers.
- DNOs must regularly report on their actions to deal with electricity theft and publish information on these actions.
- Suppliers' licences have been amended to strengthen their obligation to investigate, detect and prevent electricity theft.
- Electricity suppliers were also directed to implement, by February 2016, a central service to assess the risk of electricity theft at consumer premises. This will help target theft investigations.

# 4 Methods to decrease losses

Comprehensive reviews of loss reduction techniques were carried out by CIRED WG-2015-2 [29] and by Kalambe and Agnihotri [30]. The techniques are broadly split into three categories: capacitor placement, network reconfiguration, and distributed generator allocation.

## 4.1 Capacitor Placement

Capacitors act as a source of reactive power; by placing a capacitor in parallel to a line, its inductive reactance is reduced, which leads to a reduction in losses. The main challenges identified for this technique are:

1. selection of an appropriate number of capacitors
2. siting of capacitors
3. sizing of capacitors

The capacitors will often serve multiple functions, because they will affect the voltage and power flows as wells the losses. Research into capacitor placement dates from 1956 through to 2008, with more sophisticated optimization techniques being developed to size and allocate the capacitors within the network. In early research, capacitors were installed as a fit-and-forget solution, but more recently switchable capacitors have been studied, which allow active management of network losses.

## 4.2 Network Reconfiguration

Network reconfiguration is the process of altering the network topology through switching actions, either closing normally open points or opening normally closed points. Much like capacitor placement, network reconfiguration serves several functions:

1. Re-connecting customers under unplanned outage conditions
2. Load transfer to conform to current or voltage limits
3. Planned outages for maintenance
4. Loss minimization

Conventionally, network reconfiguration has been considered using either branch exchange – in which switches are operated in pairs to ensure radial operation – or loop cutting – in which the system is initially completely meshed, and switches are opened until a feasible radial configuration is reached. More recently, techniques have been developed which use node-based algorithms to identify optimal network configurations for a given objective. Wen et al. [31] propose a strategy based on node importance, which is characterised by the number of branches emanating from a given node; the algorithm proposed matches conventional approaches when minimizing power loss is the only objective. A node-depth encoding approach was proposed by Santos et al. [32]. In this method, the nodes are stored in an array which contains the depth of each node – defined as the distance from the root of the tree, which are typically substations. The algorithm was able to find network configurations corresponding to power loss reductions of over 25%.

## 4.3 Distributed Generator (DG) Allocation

Embedding generators within the distribution network can lead to a reduction in network losses, thanks to the reduced power flows in some areas of the network as some customers are supplied by generators that are electrically much closer to them. However, there are also instances in which reverse power flows from distributed generators can lead to increased losses in certain scenarios. The location, generating pattern, and control of DG can significantly alter their effect on network losses. Numerous methods exist in the literature for determining the optimal size and location of DG within the network.

## 4.4 Superconductors

Superconductors are materials which have almost zero resistance in certain conditions – specifically extremely low temperatures. Consequently, the $I^2R$ loss for a current flowing along a superconducting circuit will be close to 0; a feasibility study carried out by WPD suggested that there could be an economic benefit, in spite of the higher capital and operating costs [33]. However, super conductors need to be kept at an extremely low temperature, which requires a complex cooling system using cryogenic coolants such as liquid nitrogen, consequently, they are not currently used in distribution networks.

### 4.5 Voltage Optimisation

The voltage of a distribution network has an impact on both the current flow – and therefore losses – and the loading. As many electrical loads are voltage dependent, by reducing the voltage the power, and therefore current, demand can be reduced, leading to a reduction in losses. However, if the loading is not voltage dependent – which is increasingly becoming the case with switched mode power supplies driving appliances such as LED lighting, computers, and motors with variable speed drives, then this approach could instead lead to an increase in current, and a corresponding increase in $I^2R$ losses [34]. Consequently, setting the optimal voltage to minimise losses is non-trivial, and the optimal voltage itself can vary with time of day.

### 4.6 Energy Storage and Inverter Control

Due to the increasing uptake of solar photovoltaics and energy storage, and the advent of the soft open point (SOP), power electronic inverters are becoming more prevalent within distribution networks. These inverters can fulfil similar functions to capacitors, through acting as sources or sinks of reactive power, they can reduce circuit reactance and therefore reduce losses within the network [35]. Three phase inverters can also correct load imbalances [36], which leads to a reduction in losses because of the nonlinear relationship between line current and electrical loss.

Energy storage systems bring additional advantages; the inverter advantages described in the previous section are augmented by a dispatchable source and sink of real power, which can be used to reduce peak power loss, leading to a reduction in overall energy loss [31]. This has been taken further in some studies, through optimal placement of the energy storage system [37] and experimental validation [38].

Soft Open Points (SOPs) can fulfil the function of capacitor placement and network reconfiguration simultaneously. An SOP is a bidirectional power electronic device which is used in place of a switch at a normally open point. These devices can be used to compensate for imbalance within the network [39] and to manage the losses in a network with high penetrations of domestic PV, which are potentially distributed unevenly between the phases of the network [40]. Although there is an operating loss associated with using SOPs for this purpose, Bloemink and Green [41] have defined a minimum converter efficiency required to ensure a positive impact on overall system losses.

### 4.7 Summary

The majority of academic research in this area consists of optimisation algorithms used to reduce network losses in a given set of conditions (i.e. a peak power loss). The focus is primarily on development of these algorithms, and the technologies which are enabled, rather than enhanced understanding of network losses, which is in fact essential to any algorithm which seeks to minimise losses within a distribution network.

# 5 Review of DNO Activities on Network Losses

On the whole the losses strategies of each of the UK DNOs [22, 42-46] are broadly similar as commented upon in Northern Powergrid's most recent losses strategy. This section of the literature review will provide a brief comparison of the significant methods by which DNOs are managing losses within their licence area.

Where a DNO has a particular project which is investigating losses in greater detail this will also be highlighted.

## 5.1 Technical Loss Reduction Strategies

### 5.1.1 Asset Replacement

#### *5.1.1.1 Transformers*

Each of the DNOs has identified a need to replace any ageing units which are still in service, with a typical cut-off date of around 1960. The EU EcoDirective for transformer capabilities is held as the yardstick for performance, with many of the DNOs actively attempting to outperform these requirements for any newly procured transformers.

<u>ENWL</u>

- Not cost effective to replace large grid, or primary transformer units.
- CBA does support the replacement of older transformer units and as such 489 1000kVA units and 163 800kVA ground mounted units are scheduled to be replaced

<u>WPD</u>

- WPD has replaced 1996 pre-1958 transformers with a projected saving of 21GWh at an annual cost of around £2m.
- Identified that after CBA was carried out on 500, 800 and 1000kVA transformers in the 11kV system, 249 transformers showed merit in being oversized, saving around 812MWh in losses saving £1.38m.
- Benefit has been shown in universally upsizing the typical minimum size ground-mounted transformer from 315 to 500kVA.

<u>SSEN</u>

- It is noted that any benefit from increasing minimum transformer size represents a 'marginal case' however standard practice will be to enforce 500kVA and 50kVA as the minimum sizes for ground and pole mounted transformers respectively.
- Have more than 3000 secondary transformers in service which were manufactured pre 1960.
- Intention is to target 50% of 1200 transformers scheduled for replacement during ED1 at a saving of 25,650 MWh.

<u>UKPN</u>

- Replacement of large grid or primary transformer units does not represent a viable option.
- The cost of introducing low-loss Amorphous Steel-Cored Transformers as general practice cannot be justified but are noted as a potential option should economies of scale become more significant in their favour.

<u>SPEN</u>

- More cost effective to undertake on-site refurbishment of grid, or primary transformers as opposed to replacement
- SPEN has identified 1,111 transformers which incur high losses and is to pro-actively replace these units during ED1
- SPEN will not replace pole-mounted units for loss improvement, and will continue to replace based on failure

- This policy will continue to be evaluated to determine if replacement of high-loss units in conjunction with other planned activities is of merit.

NPg

- Examining the feasibility of using Amorphous Steel-Cored Transformers
- Cost benefit analysis showed that current policy for transformer procurement gave the best CBA against adopting the EU EcoDesign policies directly.
- Replacement of 3517 pole mounted transformers is expected to deliver a benefit of 4.9GWh during ED1
- Replacement of 3317 ground mounted transformers is expected to deliver a benefit of 142.9GWh during ED1

#### 5.1.1.2 *Overhead Lines*

None of the DNOs have stated that replacement of overhead lines in their network based on the grounds of losses improvement represents a positive CBA.

In particular SPEN noted that typically, existing pole infrastructure in high loss EHV circuits, would likely be incapable of supporting the additional weight of increased conductor cross sectional area. This means that wide-scale reconductoring and pole replacements would be required, negating any overall cost benefit.

At HV, SPENs policy is to ensure all newly installed overhead lines have a cross sectional area of 100mm$^2$. NPg performed a CBA of increasing the standard spur cross sectional area from 50mm$^2$ to 100mm$^2$ as standard and rejected this due to a negative CBA. There is scope to review this policy however as the potential loading from LCTs increases across the licence area. Across each of the DNOs a case-by-case approach to replacement of overhead lines is present.

#### 5.1.1.3 *Underground Cables*

- Concerning underground cables, none of the DNOs identified a rationale for active replacement of their existing assets. Recommendations have instead been made for so-called opportunistic replacement policies.
- The key policies across all of the DNOs are outlined in Table 3.

| DNO | Voltage Level | | | |
|---|---|---|---|---|
| | **LV** | **11kV** | **20kV** | **33kV** |
| ENWL | 300mm$^2$ as more cost effective than 95 and 185mm$^2$ | | | |
| WPD | Tapering discontinued<br>95mm$^2$ discontinued | 95mm$^2$ discontinued | | 240mm$^2$ replaced by 300mm$^2$ |
| UKPN | Tapering constrained<br>Case by case for increasing asset size | Case by case for increasing asset size. 300mm$^2$ now the smallest installed in line with design policy at 33 kV. | | |
| SSEN | 95mm$^2$ replaced by 185mm$^2$ | 70mm$^2$ replaced by 150mm$^2$ | | |
| SPEN | Case by case for increasing asset size (Actively considering a policy in this area) | | | |
| NPG | 300mm$^2$ waveform | 300mm$^2$ Triplex | 185mm$^2$ | |

*Table 3: Underground Cable Policies for each UK DNO at commonly used voltage levels*

UKPN notes that 132/11kV transformation could have significant impact by removing an additional transformation layer, however raises the point that such transformation may result in excessively large 11kV switchboard boards and/or excessively long 11kV feeders.

### 5.1.2 Reduction of LV Voltages

The LV Templates project identified that approximately 82% of UK LV networks can be described by the 10 template networks which were developed. This project also identified that reduction in LV voltages could lead to a subsequent reduction in network load. WPD has reduced demand in its LV networks by 1.16% due to a slight reduction of the LV voltage.

NPg comments that it is considering voltage reduction during the night, however states that more work is necessary in this area to ensure that losses are not in fact increased.

### 5.1.3 LV Phase Imbalance

WPD’s Losses Investigation project is analysing imbalance throughout the LV network including at substations. They have identified through use of their pre-existing network of LV Templates substations that imbalance in the LV network can lead to neutral currents which are roughly 35% of the phase currents or higher. SSEN has plans to install static balancers in long LV feeders with a potential saving of 1042MWhs per year, although the potential number of installations in ED1 is expected to be small. The area of phase distribution at LV is outlined as a potential area for SSENs dedicated losses team to examine within ED1. NPG notes in their losses strategy that these have been installed in legacy networks within their licence area, and they intend to keep a watching brief as to developments from SSEN.

UKPN notes that imbalance can often be high in LV overhead line networks, since the lower blue phase is often the easiest to connect to, and therefore can become easily overloaded. As part of its ABC reconductoring project, UKPN is actively working to correct this imbalance. UKPN is also undertaking work to renew its LV link-boxes, which it is using as an opportunity to assess the potential to relocate LV NOPs where appropriate.

### 5.1.4 HV Phase Imbalance

WPD is investigating the use of an HV connected solar generation customers’ inverter in combination with an electrical energy storage unit in order to correct phase imbalance on the HV system. This work is being carried out as part of the NIA funded Solar Storage project.

UKPN as part of its ABC reconductoring program is actively seeking to remove traditional phase balancers where possible from their 11kV network, as these can contribute to overall network losses.

### 5.1.5 Power Factor Correction

Recommendation 2 from the SOHN report was for DNOs to consider data gathering with regards to assessing network power factors. Each of the DNOs has acted upon this recommendation with varying extent. WPD as noted previously is investigating the capability to address power factors in the 33kV network through the use of PV inverters. UKPN states that it will actively seek to derive new measurements of power factor and will examine NIA and NIC funding in order to investigate the latest techniques which become available during ED1. NPg notes that it is to use the outputs from its LV monitoring board project in order to more accurately assess power factor at this level. SSEN, NPg and ENWL state that their CBA did not merit the active installation of power factor correction within their networks.

## 5.2 Smart Solutions for Loss Reduction

### 5.2.1 Dynamic Thermal Ratings

A number of DNOs refer to the potential introduction of dynamic thermal ratings into their network operation techniques. It is commented upon however that by increasing utilisation of assets there will be a natural increase in network losses. This represents a need to make careful analysis of the trade-off between reducing the need for asset replacement or reinforcement and the resultant increase in losses. WPD's FALCON project analysed dynamic thermal ratings of power system components which the DNO is now considering whether to deploy across their licence area.

### 5.2.2 Demand Side Response and Smart Meter Data

A number of DNOs have projects which examine the effect of demand side response such as SSEN's ACCESS and SAVE projects. DNOs, perhaps somewhat prior to the emergence of the DSO transition appear to consider DSR as a technique beyond the control of the DNO.

UKPN commissioned a study from Imperial College London which determined that based upon optimum demand flattening through DSR, there is the potential to deliver an additional 15% increase in energy demand. Their projections estimated that the uptake of electric vehicles was likely to require an increase of around 19% and therefore could be within the remit of DSR to provide this network headroom.

A concept which could fall under the category of demand side response is that of the smart charging of Electric Vehicles. Only one DNO (SSEN) makes comment towards this explicitly, referring to the outputs of their 'My Electric Avenue' project.

Smart meters are acknowledged by all of the DNOs as being crucial enablers of demand response, and thus the ability of DNOs to have access to and to work with smart meter data is of significant importance.

Data from smart meters has a number of roles to play in any future assessment of network losses in both the technical and non-technical categories. A summary of the main areas in which smart meter data could play a role is as follows:

- Identification of areas with significant losses or those with rapid demand growth to determine where cost effective solutions may be deployed.
- Work with suppliers examining suitable demand side response or time of use tariff schemes for consumers
- Reduce non-technical losses by reducing transactional theft from the network and improving overall revenue protection activities
- Incorporate smart meter data into enhanced network design, planning and modelling concerning losses, improving the overall baseline for network losses.
- Improve voltage monitoring at lower voltage levels, maximum demand indicators, and substation peak loading values.
- Enablers of enhanced active network management schemes

### 5.2.3 Electrical Energy Storage (EES)

DNOs have commented that given the current cost of EES devices, it is not cost effective to install EES with the sole intention of affecting network losses. It is noted however that all DNOs aim to monitor this moving forward and will consider losses within any scheme whereby EES devices are installed for additional reasons such as UKPNs EES project at Leighton Buzzard.

#### 5.2.4 Active Network Management

Almost all of the DNOs are considering active network management as part of their overall strategy to improve network losses. A number of projects are contributing to this space, including WPD's FALCON project which examined automated load transfer (ALT) [47] schemes in combination with dynamic asset ratings and the introduction of electrical energy storage. Another project examining this automated reconfiguration is SSENs Low Energy Automated Networks (LEAN) project.

ENWL's Smart Street and Capacity2Customers projects are considering dynamic operating regimes for customer connections

Soft Normally Open Points, or the reconfiguration of the network as a means of reducing losses is discussed by many DNOs. UKPN's work within the Flexible Plug and Play Networks project is outlined as being key in building confidence in the required 'frequent use' switchgear required to enable this level of active network reconfiguration.

#### 5.2.5 Transformer Auto Stop Start / Switching out of under-utilised plant

A number of DNOs have considered the potential benefits of switching out under-utilised transformers in their network. The LEAN project from SSEN is investigating this potential directly, with each of the other DNOs commenting that they are waiting for analysis from this project before considering deployment within their own licence areas.

WPD note that for their 11/33kV transformers this would not be suitable due to the reduced security of supply, although a number of other DNOs have commented that this switch-out of plant would be accompanied by appropriate network switching in order to maintain supply integrity.

#### 5.2.6 Non-Technical Loss Reduction Strategies

Each of the DNOs have a number of policies which aim to minimise non-technical losses in their licence area. With regards to the theft of electricity from the network typically these are broadly similar and will therefore not be commented upon in particular.

Some DNOs operate specific teams to investigate these instances, collaborating with local law enforcement or other stakeholders. One point of note is that WPD has identified over 8000 cases of illegal network use, leading to an overall network saving of around 2.8GWh of losses.

The other significant area of consideration with regards to non-technical losses are unmetered supplies. As noted in the introduction to this literature review, there are a number of different reasons behind unmetered supplies. A number of DNOs note that they are to carry out more work with regards to evaluating the introduction of metering for some of these supplies and/or carrying out a more detailed audit of their unmetered supplies. Some DNOs also categorise substation electrical demands as non-technical, and are therefore included as part of the audit, or smarter solutions such as waste-heat recovery are being investigated as part of addressing these system losses.

## 5.3 Losses Discretionary Reward Tranche 2

This section examines each of the DNOs recent Losses Discretionary Reward [48] submissions for Tranche 2 (LDRT2) [49]. As per the overall losses strategies, there are many similarities between the LDRT2 submissions therefore the focus here will be on identifying the key areas and outlining any potential gaps against Northern Powergrid's most recent submission.

### 5.3.1 Contact Voltage Losses

Within the recent LDRT2 submissions, the finding with potentially the greatest impact is the declaration by UKPN of a potential new class of network losses, which are not capable of being described as an additional technical or non-technical loss; Contact Voltage Losses (CVL). These are so-called as they occur as a result of stray voltages due to faults in the LV system which members of the public may come into 'contact' with.

Their estimation, independently analysed by Princeton University, estimates that a total of 590GWh is lost within the UK system due to CVL. These losses have been detected due to UKPNs introduction of Mobile Asset Assessment Vehicles (MAAVs). These are also due to be evaluated by SPENas part of their Tranche 2 activities.

### 5.3.2 Smart Meter Data Analysis

Perhaps the most commonly highlighted theme across all DNOs is evaluating the use of smart meter data in network loss estimation. Each of the DNOs appear to retain some concern as to the speed of the smart meter rollout and its resultant impact on loss estimation, with many activities concerning the use of these data being pushed into the ED2 period.

Whilst preparing for the smart meter rollout, a number of DNOs have carried out projects or commissioned studies which aim to estimate the impact of metering in the future. A Strathclyde University study carried out for SSEN has estimated that even with a 10% penetration of available smart meter data within an LV network, 'reasonable' estimation of losses can be made.

SPEN has a potentially interesting project which considers the feedback of domestic voltages from smart meter data into the overall AVC scheme for the 11kV network. This could form part of an additional AVC scheme which would operate in conjunction with high PV penetrations in the LV network.

Northern Powergrid's project with the University of Sheffield has also considered the impact of smart meter data time resolution on network losses.

SSEN has also collaborated with two companies, BC Hydro and their energy supplier Awesense. This collaboration examined the impact of smart metering data on overall revenue protection. BC Hydro has seen reductions of 850GWh in terms of electricity theft and a resultant 50% reduction in network losses. These savings have been directly attributed to the high penetration of smart meters within their licence area.

### 5.3.3 Losses in the DSO environment

Whilst each of the DNOs have referred to the emerging role of the DSO transition within their LDRT2 submissions and the potential impact that operating as a DSO may have on losses, two DNOs (SSEN and UKPN) have projects which have a specific focus on delivering results which are comparable to actual operation as a DSO.

SSEN is collaborating on the Smart Fintry project, which analyses community owned generation and local energy trading as a specific example of a future local energy market and as part of this project is evaluating the impact of this style of operation on network losses. This project is evaluating a number of potential future network loading scenarios and therefore the outputs of this project may be of particular value.

UKPN's Power Potential project which examines the interface between the Transmission and Distribution Systems, is also noted as being a reference for managing losses within the complex DSO environment.

### 5.3.4 Heat Recovery from Substations

A common theme across each of the LDRT2 submissions is the consideration of waste heat recovery within substations. UKPN's pilot Bankside study is often referred to as being the first evaluation of this technique.

Northern Powergrid has contracted the same consultancy firm as used by UKPN in order to evaluate the technique within Northern Powergrid's area.

Both SSEN and SPEN have additional projects coming under the heading of substation efficiency, where waste heat recovery is being considered as part of an overall efficiency improvement, however WPD have rejected any further investigation of waste heat recovery as they believe as a result of their analysis, that there is minimal potential gain from employing these techniques under the present framework.

Whilst not specifically within the domain of heat recovery, ENWL's Celsius project is examining the potential to cool power transformers in an attempt to increase network headroom.

### 5.3.5 Cross Border Loss Reduction

Typically, each DNO has managed losses within their own particular licence area. SSEN and UKPN have joined together on a project which is investigating the potential to achieve increased performance with regards to losses by evaluating a cross border approach whereby at the edge of the licence area, increased efficiencies can be made by considering losses in a combined manner.

As noted in SSEN's submission, improvements considering existing customers were limited, however increased benefits were observed when considering new larger customer connections.

### 5.3.6 Optimisation within LV networks

UKPN have trialled the powerPerfector iQ at the Power Networks Demonstration Centre (PNDC), achieving a 17% reduction in losses within a typical LV trial network [50]. Losses in networks at higher voltages have also been observed. The device raises or lowers the network voltage in order to optimise for the series of loads in the network at a particular point in time.

WPD have considered the shortening of LV feeders in order to optimise LV network design for the integration of LCTs in future. This 'shortening' was carried out by increasing the density of transformers within the network. The study carried out concluded that in some cases loss reductions could be made, but in one of the case study networks, losses actually increased as a result of this change in configuration.

### 5.3.7 Fuse Failure Detection

SPEN noted in their submission that earlier detection of fuse failures in the meshed LV network would reduce losses and improve security of supply. They have established a project which aims to detect these fuse failures through the use of smart meter data. A prototype method capable of detecting these failures has been developed with a plan to test the method further as the smart meter rollout progresses.

#### 5.3.8 Service Cable Losses Mapping

SPEN also has a project in which it overlays their service cable parameter information with GIS information of the network in order to develop a heat map for losses in the overall service cable network.

#### 5.3.9 Power Electronics Transformers for LV supply at HV

WPD is considering the use of Power Electronics Transformers in order to supply LV loads from the HV network for LCTs such as electric vehicle charging. The aim of these transformers would be to reduce losses in the LV network by supplying the potentially large charging loads directly from the HV network.

#### 5.3.10 Retrofitting of 3 phase supply for phase balancing at LV

WPD is also considering the retrofitting of 3 phase supplies for existing single phase customers. This comes under the label of HV charging at the driveway.
This could allow active balancing of the LV network in future, thus attempting to mitigate a significant source of losses.

# 6 Scope for improving the handling of losses

In this section, the scope for new contributions to enable enhanced understanding of network losses is discussed, based on the industrial, academic, and regulatory content which has been reviewed in the previous sections.

## 6.1 Impact of present and future network scenarios

In any given network scenario, the overall network losses are influenced by a number of factors. The most significant of these – based on the academic literature – is the temporal and spatial variability of electricity demand. The size and duration of the demand peak relative to the base demand has a substantial impact on network losses because of the inherent $I^2R$ law. This can be further exacerbated by the inclusion of distributed generators within the network. The diversity and type of demand also contribute to the complexity of the required calculation - industrial demand presents a particular challenge since each customer has a relatively unique load profile.

There is no clear example in the literature of a method to enable loss forecasting. Losses will be directly impacted by changes in network demand, but they will also be affected by the uptake of low-carbon technologies, the increase in harmonics caused by power electronic devices, and potentially time of use pricing enabled by smart meters. There is a potential that poorly designed time of use tariffs might have a material effect on load diversity and therefore the associated losses.

## 6.2 Impact of Smart and non-Smart Technology

The impact of individual smart interventions has been investigated – at least to some extent – within the literature. Electric vehicles, DG, energy storage and smart loads – potentially enabling demand side response services – can have a material impact on losses. Some of these technologies have the potential to reduce network losses, but only if appropriate incentives exist; in other cases, Smart Grid interventions such as ANM could lead to an increase in network losses if they are fulfilling another objective, for example accommodating non-firm wind or additional demand customers. With the exception of vehicle-to-grid charging, EVs will increase network losses. However steps can be taken to reduce their impact, including through harmonic reduction and incentivising charging during off-peak periods.

Smart technologies can enable several loss reduction techniques, including dynamic reconfiguration and phase rebalancing, the use of soft open points to balance demand between feeders, and the use of smart meter data to calculate losses more accurately and precisely.

## 6.3 Impact of measurement errors

Measurement errors lead to lower accuracy in loss estimation. It is important to understand the extent to which this has an impact on the design, planning, and operation of the system – something which is largely omitted from the existing literature. Sensitivity analyses should be carried out to understand the impact of measurement errors on estimated network losses. WPD report that the use of $I^2R$ estimation is more accurate than calculating the difference between power sent and received; the sensitivity analyses will enable evaluation of this claim. There is also scope here to investigate the accuracy of the assumed impedance values in network models, how these vary in the short term with environmental conditions, and in the long term as equipment ages. Finally, it is essential to understand how these errors could impact on decision making, varying from replacement or reinforcement of existing assets, to whether to change the tap position on a transformer.

## 6.4 Impact of monitoring at multiple aggregation levels

Losses can be calculated based on measurements taken at different levels within the network. Using values from larger aggregations of customers at higher voltages has the advantage of being less labour intensive but may have a significant impact on the accuracy of the resulting loss estimation. The increase in accuracy by using higher data granularity should be quantified through a number of case studies, which could be carried out as part of the sensitivity analyses proposed in section 5.3. The analysis should be mindful of the diminishing return from the installation of additional measurement points.

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