V2G Dynamic Headroom Control

Site Selection Report

Version 2

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Contents

1. Introduction

This report describes the site selection process for the Network Innovation Allowance (NIA) funded project ‘V2G Dynamic Headroom Control’.

Dynamic and local control of active and reactive powers of Vehicle-to-Grid (V2G) within LV networks can help facilitate accommodation of all Low Carbon Technologies (LCTs), benefiting local customers and providing increased flexibility services to system operators, while minimising reinforcement costs and optimising fairness between customers. However, V2G connections can increase levels of power exports, potentially pushing voltages beyond statutory limits and/or exceeding thermal limits. This project will use smart meter data to provide improved visibility of the existing capacity headroom along the length of feeders, and to improve the targeting in location and time of active and reactive power management of V2G, while improving the confidence that assets will remain within thermal and voltage limits. This allows the existing headroom to be utilised wherever possible, minimising the need to constrain exports, and sharing the available capacity more equitably between customers.

A range of domestic LV substations and feeders across the four NGED license areas will be included as case-study examples and this document describes the method used to select these substations.

This work was initially expected to begin by specifying sample areas of the NGED license areas for which network data would be requested. A set of around 100 distribution substations within these network areas would then be selected for use in the project.

By obtaining the network data first, it would be possible to select substations for which a high proportion of the customer locations have close proximity to the LV feeder that is recorded in the CROWN asset database. This reduces the risk of inconsistencies in the aggregated smart meter data where an incorrect set of meters is selected based on the LV feeder connections from CROWN.

In practice it has been possible to obtain LV circuit topology network data for the entirety of all four NGED license areas, such that it is not necessary to specify samples areas within this. However, a sample set of substations is still required so that the work associated with the smart meter data request and the subsequent analysis work is manageable.

Additional data has been received from NGED in which substations have been rated with regard to their risk or vulnerability to high levels of connected generation. Given the wider scope of the network data, it is also now possible to consider substations from across the four license areas, prioritised by the given risk factors.

It will still be necessary to ensure that the network data and the CROWN asset records are sufficiently consistent. However, it has been decided that smart meter data can be requested for a greater number of substations, accepting the risk that some of the analysis may not be possible at some substations of the CROWN and network data are found to be inconsistent.

A series of acceptance tests have been defined to identify substations and LV feeders where there is good consistency between the CROWN records and the network data.

The site selection process therefore aims to select a variety of substations from across the four NGED license areas where the connected generation has a higher chance of exceeding the feeder capacity, either due to voltage or thermal constraints.

2. Substation risk assessments

The substation risk assessment data has been prepared by NGED DSO secondary network team, based on a listing provided by NGED IT&D team of substations with at least 50% coverage of smart meters.

For each substation, this risk rating data includes:

- Substation asset id
- License area (EMID, WMID, SWEST or SWALES)
- Number of MPANs (customer connections)
- Numbers of smart meters
- Numbers of generators (as far as is known)
- A risk factor based on proportion of customers with generators
- Transformer mount type, either ground-mounted or pole-mounted
- Transformer installation date (the age of the network, or at least of the transformer)
- Number of transformers
- Transformer rating, kVA
- Connected generation capacity, kVA (as far as is known)
- A risk factor based on the generation capacity as a proportion of the transformer rating
- Network length, m
- A risk factor based on high network length
- Length of underground cable with small cross-sectional area
- Length of overhead line with small cross-sectional area
- A risk factor based on long lengths with a small cross-sectional area
- An overall risk factor based on a weighted combination of the other risk factors

Underground cables and overhead lines with small cross-sectional area are those associated with a set of cable types listed in Appendix B.

The network length is understood to be based on the distance between the substation and the most distant customer. This has presumably been calculated using the CROWN customer location records, although it is unclear how this method has avoided very long distances being calculated where the CROWN records have customers assigned to the incorrect substation. The use of a radial length, rather than a length along the route, will also under-estimate the cable length. Some inconsistencies have also been noted in cases where the recorded lengths are very low. Some of the examples have been viewed on the NGED DataPortal2 GIS, where the radial extent of the LV feeders appears to be much greater. However, there is no reason to suspect that substations listed with long lengths are over-estimated. Even with possibly curves in the feeder route, the cables cannot be less than the reported length.

There is mostly one transformer per substation but at 0.5% of substations there either two or three transformers. The transformers are not necessarily of the same rating, but only one figure is recorded in the data. Where generation capacity has been expressed as a percentage of the transformer rating, any second or third transformers are ignored.

This risk assessment data is helpful in identifying substations where there are sufficient smart meters to enable the analysis to proceed, and where there is a reasonable probability of generation representing a constraint, either now or with future uptake of solar PV, battery storage or V2G.

Four risk criteria have been included, allowing for either thermal or voltage rise concerns:

- High proportion of customers with connected generation,
  rated as: 'High' (5), 'Medium' (3), 'Low' (1)

- High proportion of connected generation capacity, relative to the transformer rating, rated as: ‘High’ (5), ‘Medium’ (3), ‘Low’ (1)
- Long network length, rated as: ‘High’ (2), ‘Medium’ (1), ‘Low’ (0)
- Long lengths of feeders with small cross-sectional cable, rated as: ‘High’ (2), ‘Medium’ (1), ‘Low’ (0)

Each of these are score as ‘high’, ‘medium’ or ‘low’ risk, with a corresponding numeric factor, as listed above, so that the ratings can be combined.

A final overall priority rating combines these by summation into an overall weighting as a percentage score out of a total of 14. Substations are then given an overall priority as based on these percentages, as follows:

‘High’ (>50%), ‘Medium’ (>30% and <=50%), ‘Low’ (<= 30%)

3. Substation risk trends

The substation risk assessment data has been combined with coordinate data to plot the distribution of sites with an overall ‘High’ risk rating, as in Figure 1. There is clearly a higher concentration of sites in the South West, with area clusters in the valleys of South Wales and in the rural areas south west of Birmingham.

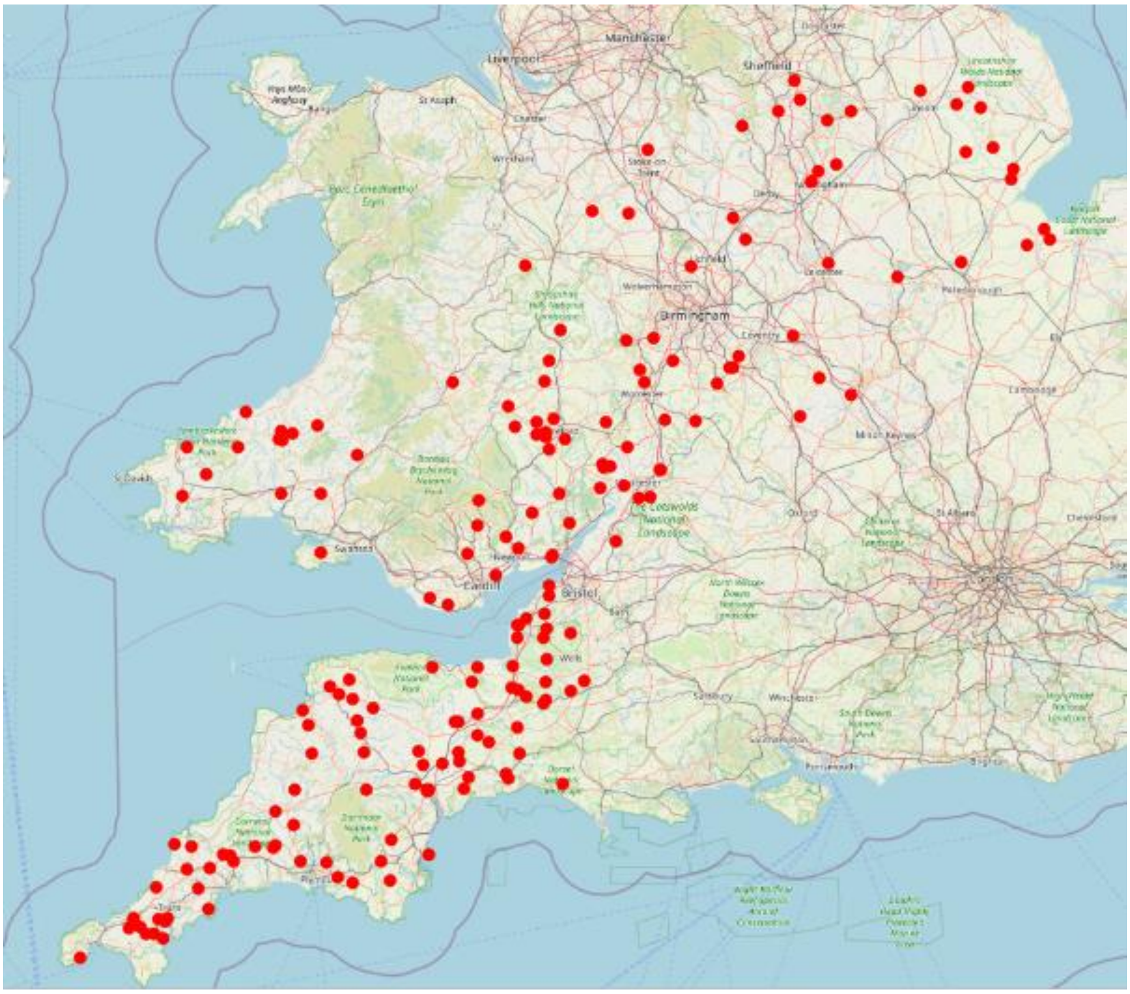

Figure 1: Substations with overall ‘High’ risk rating

Apart from the task of selecting sites for the project analysis, the risk assessment data provides useful information on the substations and the impact of generation.

As a general caveat, it should be noted that this data is already selected to exclude substations where the proportion of smart meters is less than 50%. As noted below, this will tend to bias against the inclusion of larger ground-mounted substations.

Considering just the generation, Figure 2 shows the generation capacity at each substation versus the number of generators. As might be expected, there is a clear gradient to the plotted points of approximately 3.68 kVA, consistent with the permitted export limit under the G98 connection consent.

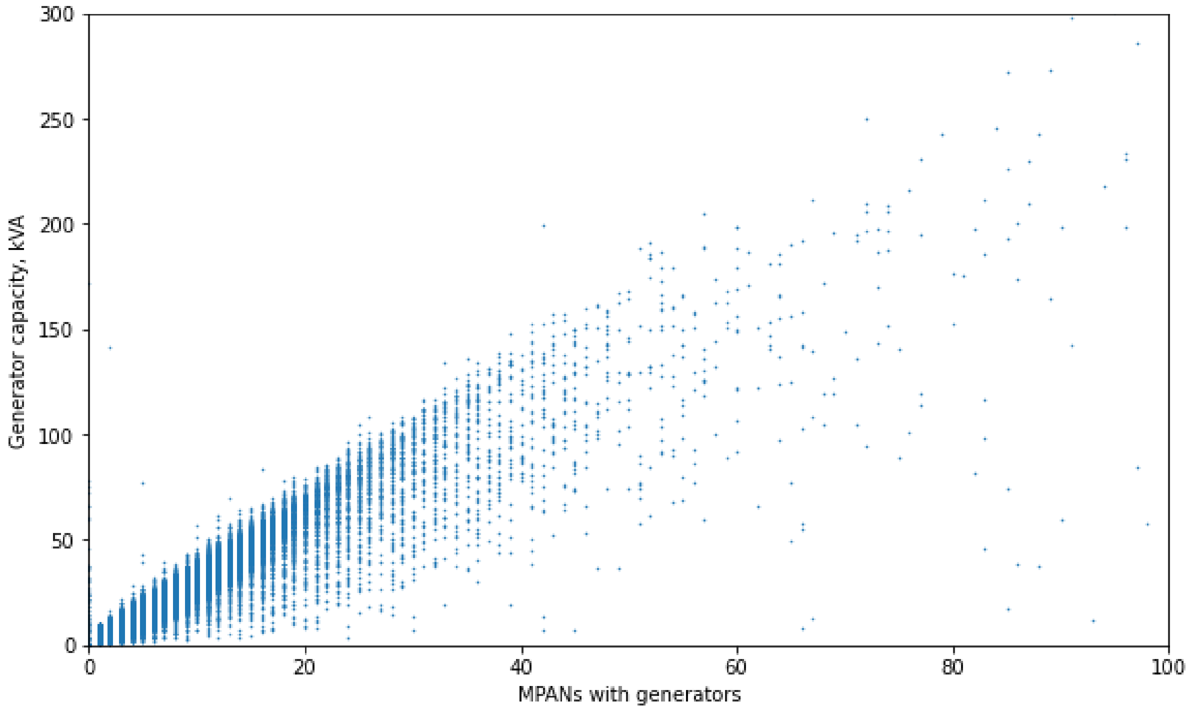

Figure 2: Connected generation capacity and numbers of generators

Averaging over the entire list of substations in the risk assessment spreadsheet, 60% of customers have smart meters, slightly higher than the national average. If the probability of a customer having a smart meter is independent from that for other customers, then it is expected that a higher proportion of smaller substations will have a high coverage of smart meters, than for large substations. For example, if assuming a 60% probability of having a smart meter, there is a 36% probability that a substation with two customers will have 100% smart meter coverage. If the substation has ten customers, then the probability of 100% smart meter coverage is only 0.6%. Any selection process that sets a minimum threshold for the number of smart meters will therefore bias towards smaller sites.

This effect can be seen in Figure 3 which shows the proportion of substations having a given smart meter coverage, plotted for substations grouped according to their number of MPANs. The plotted probability density functions are asymmetrical as no substations with less than 50% smart meter coverage are included in the data. The plot shows that if, for example, a threshold was set requiring 70% smart meter coverage, there would be decreasing proportions of substations included as the number of MPANs per substation increases.

In practice, it is not the case that the probability of one customer having a smart meter is fully independent from the probability for other customers as there are new-build development sites where every customer will have a smart meter by design. This may account for the anomalies in the curve for substations with below 20 MPANs, which could relate to new transformers added to serve a new area of housing and with relatively few customers.

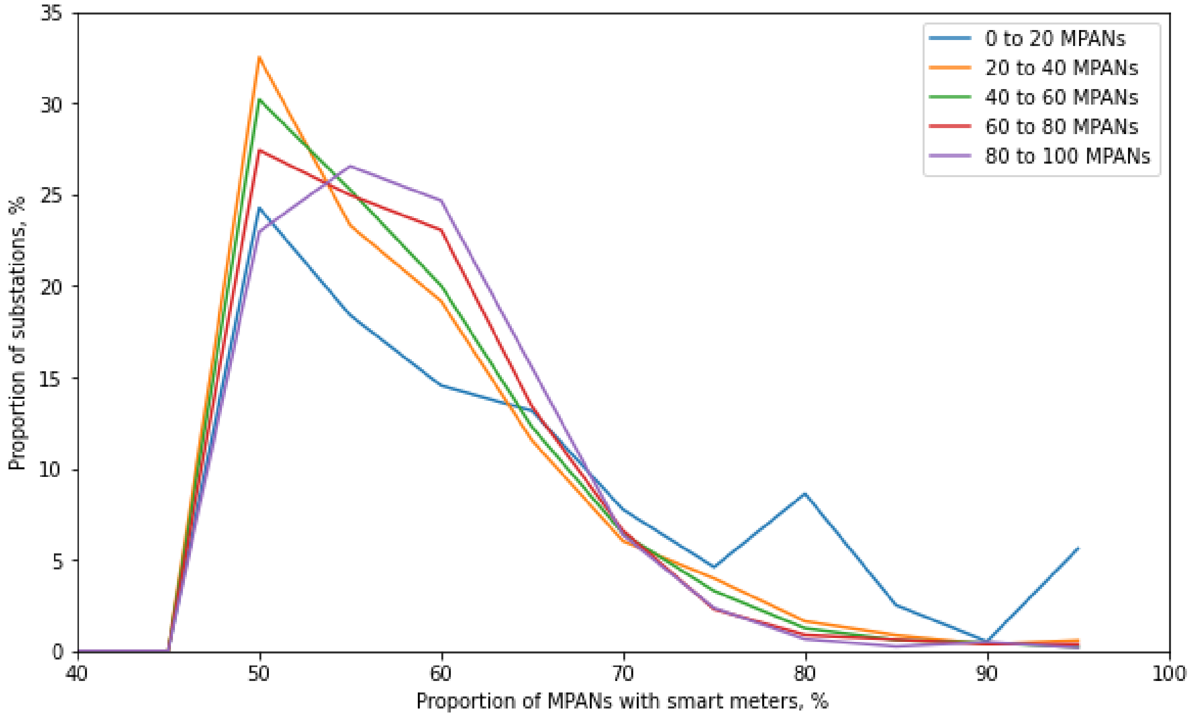

Figure 3: Proportion of substations with given smart meter coverage

A similar effect occurs in Figure 4 where the plot shows the proportion of customers with generation at each substation. Averaging over the entire list of substations in the risk assessment spreadsheet, 5% of customers have generators (or more strictly, notified generators). There are few sites with very high proportions of customers with generation, although the site selection process will emphasise these, but the trends are more visible in the plot for lower proportions. Following the same logic as above, if a threshold were to be set requiring 20% of customers with generation, this would include a greater proportion of substations with smaller numbers of MPANs.

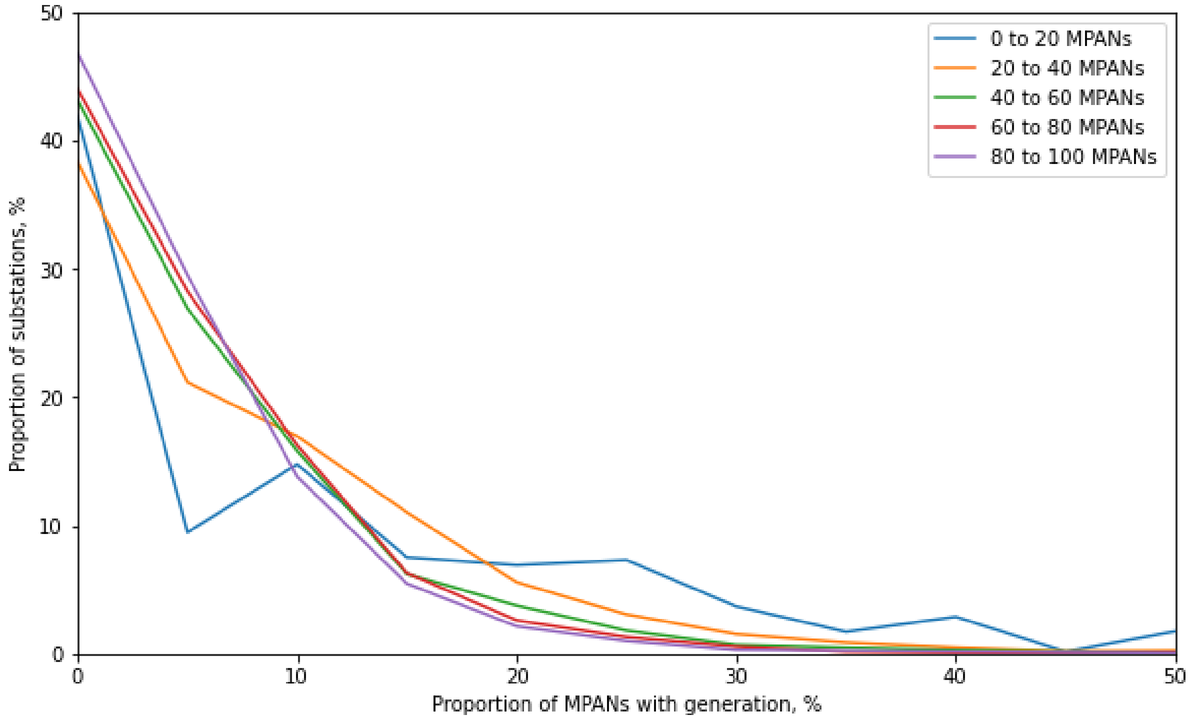

Figure 4: Proportion of substations with given proportion of generators

The site selection process will select substations with high proportions of smart meters and of generators so will be subject to this bias. However, these are also the sites where the generation represents a greater risk, assuming that the transformer and cables were not originally planned to allow for this increase in generation, so it seems reasonable that the bias should be acknowledged and then accepted.

Figure 5 shows how the mean radial network length gradually increases as the substation size increases. Simplistically, a greater radial length would be expected for substations with more customers, but these could also be serving more densely populated areas where the increase in length per customer is less. Larger substations could also have more LV feeders, not reflected here in the radial length data.

The mean length with a small cross-sectional area increases more linearly with the number of customers, as might be expected.

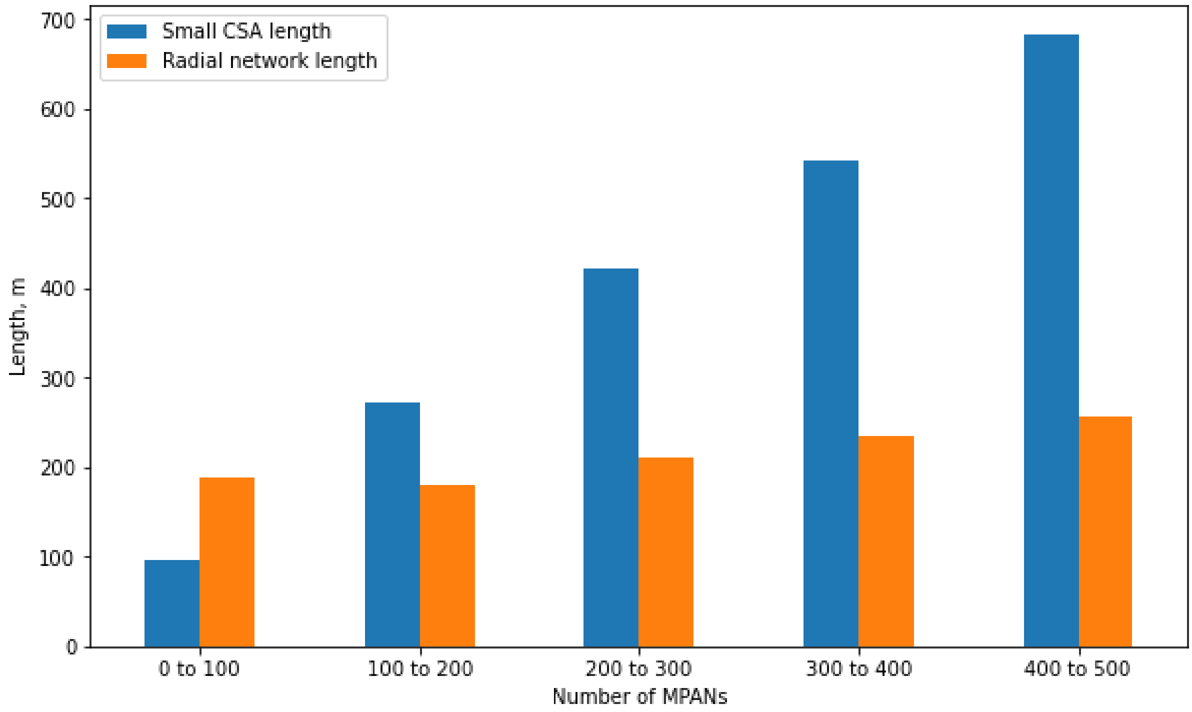

Figure 5: Network length and length with small cross-sectional area with number of customers

Figure 6 shows variations with the transformer installation date. There appears to be a trend that new substations have fewer customers, and a corresponding reduction in the number of smart meters. However, the proportion of generators rises slightly from 6% to 9% of customers. Newer substations are hopefully more resilient to connected generation, assuming cable sizes or numbers of feeders have increased over the years, but there is also a greater impact of generation that will need to be accommodated. Possibly very recent installations allow for this, but substations with transformers installed before the most recent few years presumably do not.

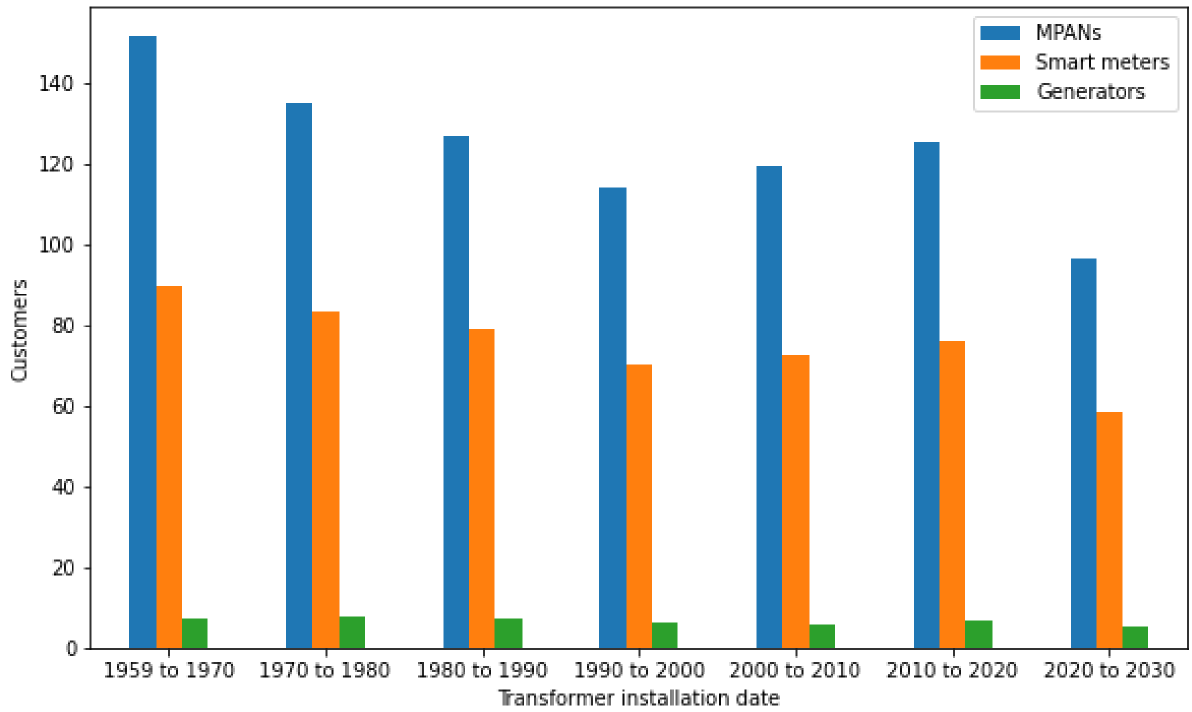

Figure 6: Generators and smart meters with transformer installation date

Figure 7 shows the mean network length data versus transformer installation date. There is a slight trend for the radial network length to reduce, consistent with the number of customers reducing as shown above.

The corresponding plot for the mean length with small cross-sectional area is shown in Figure 8. For both overhead and underground cables, the length of smaller cable sizes appears to be increasing, although the trend for underground cables seems to have improved up to 2010. It is not clear why this should be.

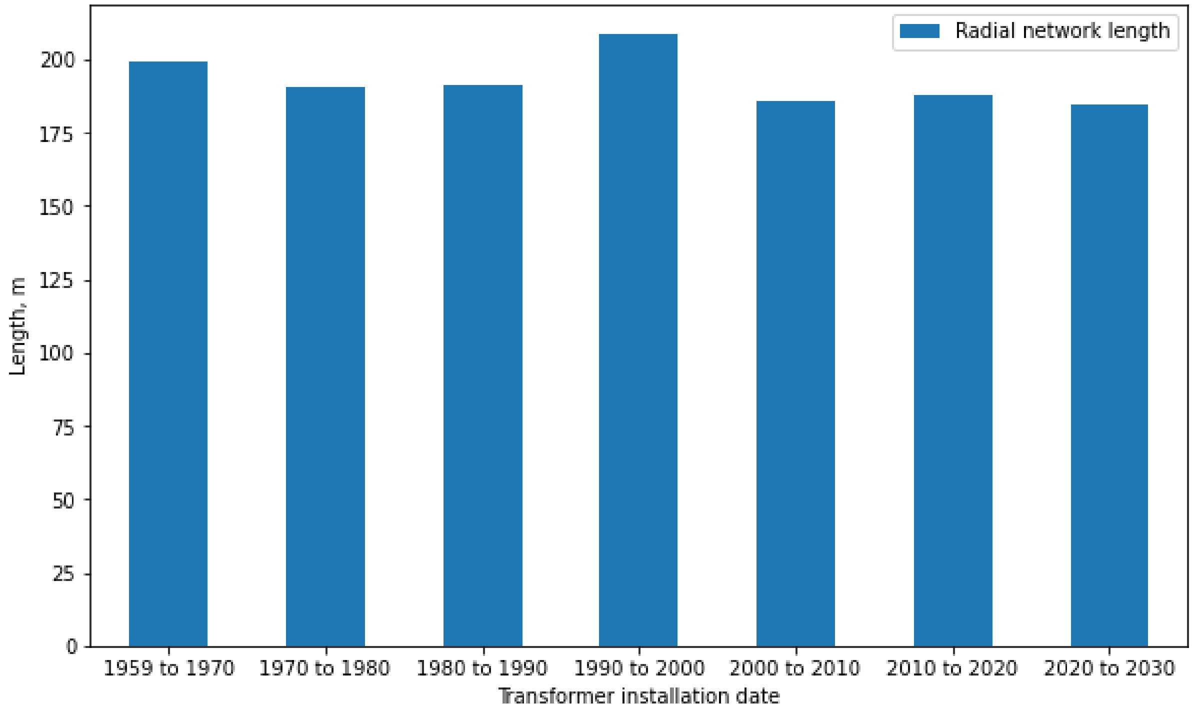

Figure 7: Network length with transformer installation date

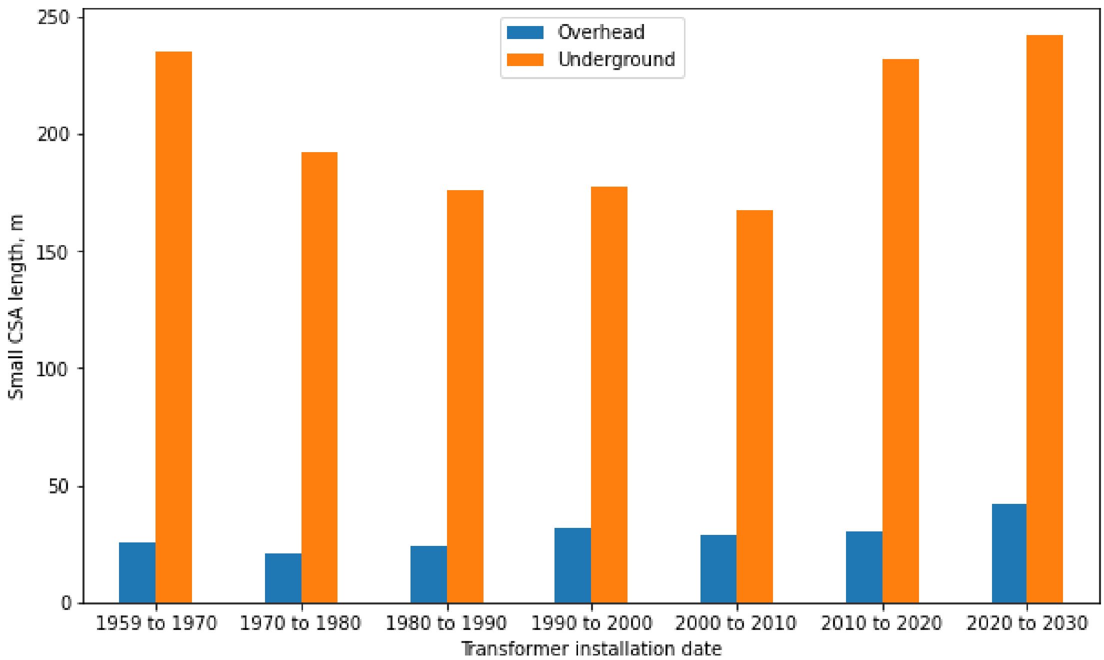

Figure 8: Length with small cross-sectional area with transformer installation date

4. Selection method

The selection method aims to find sites with high priority ratings, but also ensuring that there are sufficient smart meters to enable a successful analysis, and so that there is a diversity of substation types represented.

The overall method is set out in Table 1.

Overall priority rating

Initially, substations with a 'High' overall rating and where at least 70% of customers have a smart meter are selected. These are selected regardless of region or substation type, resulting in the following numbers of substations selected:

- East Midlands 9
- West Midlands 12
- South West 22
- South Wales 7

Smart meter coverage

Then substations with a 'High' or 'Medium' overall priority rating, and where 100% of the customers have smart meters are selected, as follows. Any substations in the above set will be duplicated here.

- East Midlands 5
- West Midlands 8
- South West 19
- South Wales 5

Including these de-risks the analysis as there is no need to allow for the unknown demands of the customers without smart meters. However, it would be unrepresentative to use only these for the analysis as it is likely that they may be new-build developments, which would ideally be less vulnerable to the growth in generation technologies, having been planned when this could have been anticipated.

Individual rating criteria

The following criteria are selected separately for each of 16 groups, intended to ensure that a variety of substation types are included in the overall set.

The set of substations is first divided into regions, giving four separate groups. These are then further divided based on whether the transformers are ground-mounted or pole-mounted, giving 8 groups. Finally, to represent a spread of age ranges, the groups are divided again according to whether the transformer was installed before or after 1980, giving a final list of 16 groups.

The selections for each of these groups are repeated for each of the criteria, in each case with the associated risk rating, as follows:

- Generator capacity as a proportion of transformer rating
- Network length
- Length with small cross-section area

In each case, initially selected substations with a 'High' risk rating and over 70% smart meter coverage.

If three or more substations meet the criteria then select the top three according to a score calculated as the product of the proportion of smart meters and the test criteria.

If less than three substations meet the criteria than repeat with either 'High' or 'Medium' risk rating.

If still less than three substations meet the criteria the repeat selecting those with over 60% smart meter coverage.

This process ensures that three substations were selected from each of the 16 sub-sections of the total set, and for each of the three individual risk criteria.

Table 1: Site selection method

Selection set	Selection metric	Method
Selections from the entire list	Overall priority rating	Includes all substations with a 'High' overall priority rating, and where the proportion of customers with smart meters is greater than 70%.
	Smart meter coverage	Includes all substations with a 'High' or 'Medium' overall priority rating, and where 100% of the customers have smart meters.
Selections from sub-sections of the list, repeated for each region, transformer mount type, and before and after 1980	Generator capacity as a proportion of transformer rating	Selection of three substations for each sub-section
	Network length	
	Feeder length with small cross-sectional area	

5. Selected substations

The process above selects 195 substations, as listed in Appendix A. The substations are distributed between the NGED regions with a higher number in the South West, as follows:

- East Midlands 42
- West Midlands 51
- South West 65
- South Wales 37

The selected substations also have a high proportion of pole-mounted transformers:

- Ground-mounted 72
- Pole-mounted 123

This compares 68% ground-mounted substations in the full data set used in the selection process. It is also likely that this data set, including only substations with at least 50% smart meter coverage, will already be biased towards smaller sites that are more likely to have pole-mounted transformers.

The ages of the selected transformers are shown in Figure 9, confirming that the selected set of substations has a reasonably representative distribution.

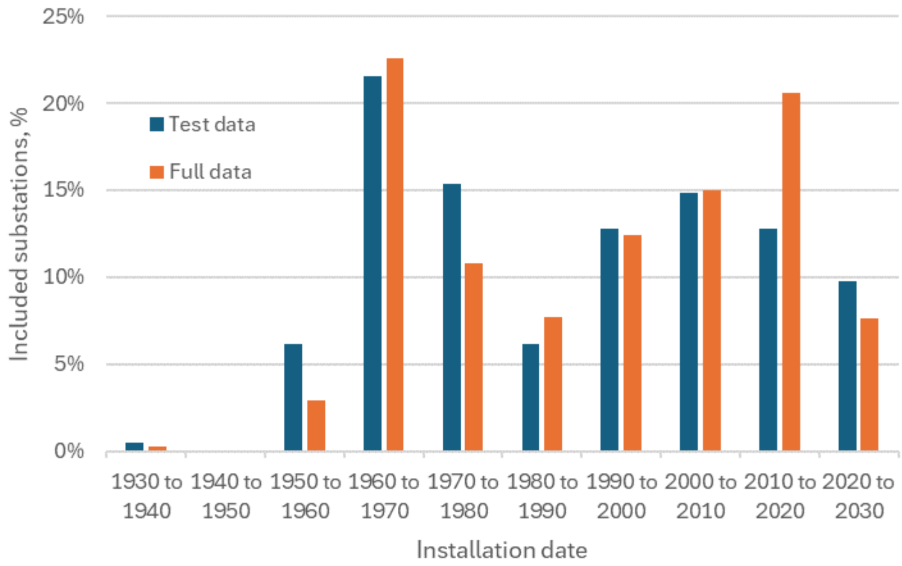

Figure 9: Installation dates of transformers of selected substations and full dataset

Figure 10 shows the numbers of MPANs at the selected substations. As expected, this confirms the bias towards smaller sites. The number of much larger sites is a more representative (although small) proportion, presumably included in the sample as the selection method requires ground-mounted sites to be included.

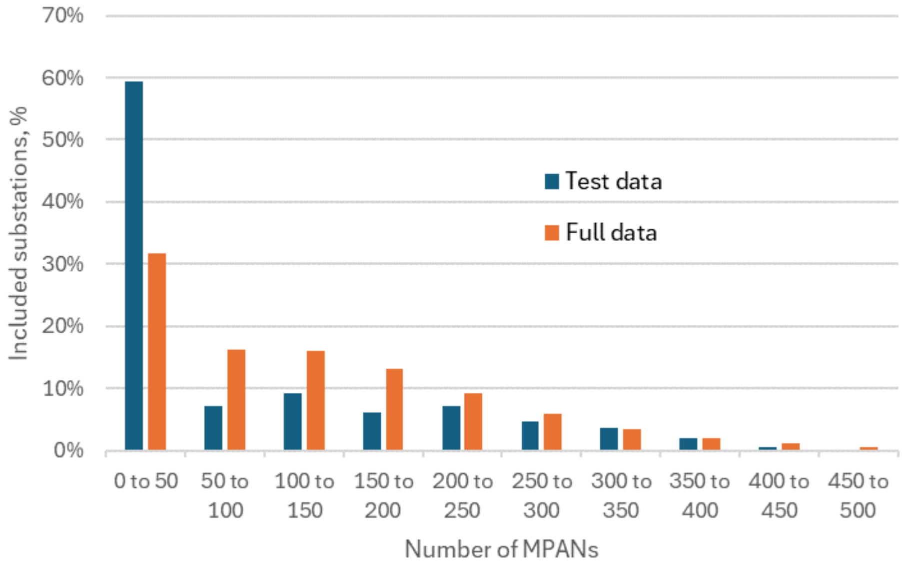

Figure 10: Number of MPANs at the selected substations

The geographic distribution of the selected substations is shown in Figure 11. The individual sites include some of those shown in Figure 1 as well as others that have been selected with regard to smart meter coverage or individual risk factors.

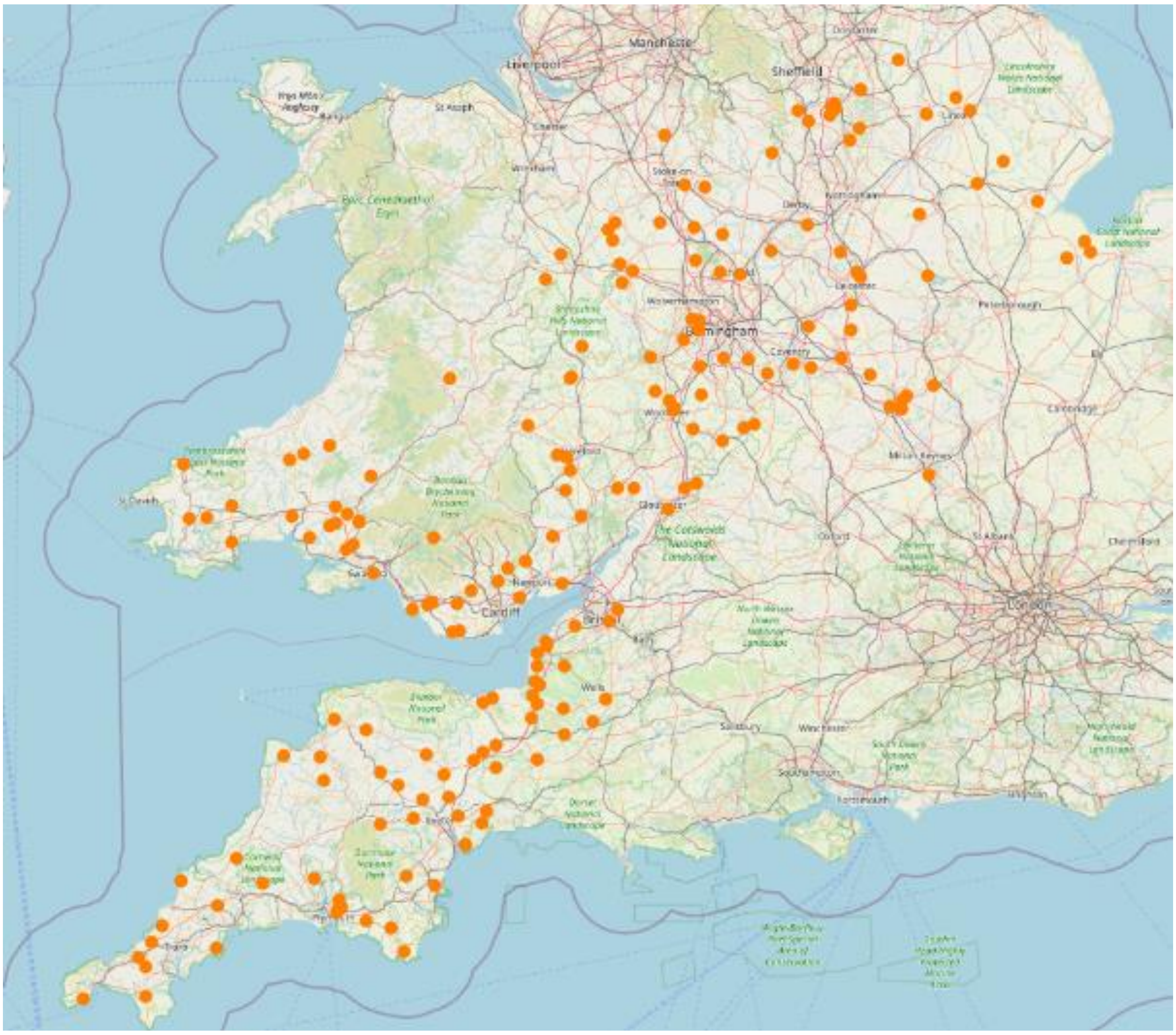

Figure 11: Selected substations

6. OLTC substations

Five additional substations have been identified where on-load tap changers (OLTCs) are expected to be installed by NGED later in 2025. These substations have been included in the smart meter data collection for this project so monitoring data before and after the installation is captured.

These five substations have also been included in the set of selected substations for this project and so will be included in the modelling work.

The substations for which OLTCs are planned are:

West Midlands

841691 St Mary’s Road	Existing 300 kVA transformer to be replaced, concerns about long HV lines and HV backfeeding
741959 Central Car Park	VisNet monitoring shows voltage limits regularly exceeded, high numbers of EVs, substation is close to primary substation which serves long HV feeders and so has a high voltage set-point

South West

410613 Churchtown St Agnes	Existing 500 kVA transformer, installed 1971, concerns about long LV overhead lines and high utilisation
310146 Shakespeare Road	Existing 800 kVA transformer, installed 1997, concerns about large numbers of generation installations

South Wales

562577 Pendrill Neath	Existing 315 kVA transformer, installed 1993, concerns about backfeeding scenarios

7. Data consistency

7.1 Proximity analysis

Inconsistencies in the CROWN records are a risk to the accuracy of the simulation work and smart meter analysis as they may indicate that customers are connected to the incorrect LV feeders. This is less of a concern with the simulation work in WP1 as, even though a model with the incorrect set of customers may not match reality, it may still represent a plausible LV feeder loading that hypothetically could exist in practice. However, if large numbers of customers are incorrectly assigned, this can lead to difficulties where the power-flow analysis does not converge due to the model including an excessively high number of connections on the feeder.

Inaccuracies in the customer connection records are a greater concern for the analysis in WP2 as this will use smart meter demand data aggregated across all the customers on an LV feeder with the aggregated set of customers being defined according to the CROWN database. Once the data has been aggregated, it is not possible to add or subtract the demands of individual customers that are found to be on different LV feeders.

A software analysis method has been developed to determine whether the customer LV feeder connections defined by the CROWN database are plausible, given the distance between the customer location and the nearest branch on the assigned feeder, as defined by the network data. This method assumes that the routes of feeder mains defined in the network data, and the locations of customers defined in CROWN, can both be treated as reliable. Although there are exceptions, previous work has found that the route data is highly reliable, and that most customer location data is also correct. Although inaccuracies have particularly been noted with location records for commercial customers, domestic connections mostly remain unchanged once installed, whereas feeder assignments can change more frequently if link boxes are re-configured, or where initial provisional information on the feeder layout for new-build housing is not updated to show the feeders that were subsequently connected.

The substation and LV feeder recorded in CROWN are referred to here as the ‘assigned’ substation and feeder. The aim of the consistency checking is to identify customer connections to these assigned feeders that are implausible, either because the distance to the feeder is too great, or where there is a feeder from another substation that is much closer.

The checks need to allow for two possible inconsistencies:

1. Customers on an LV feeder being modelled are closer to either a different LV feeder from the same substation, or an LV feeder from a different substation. These should ideally be excluded from the list of customers on the modelled LV feeder.
2. Customers from a nearby substation, or from another LV feeder at the same substation, are closer to the modelled LV feeder than to their assigned LV feeder. These should ideally be added to the list of customers on the modelled LV feeder.

Import data from CROWN is used to define the location, energisation status, and the substation and LV feeder connection for each customer meter point administration number (MPAN).

MPANs are disregarded if their energisation status is ‘D’ (inactive), and also for MPANs that are defined as export meters. It is assumed that there is a corresponding import MPAN in the database corresponding to each of the export MPANs.

Some MPANs have no record of their location coordinates and so these are also excluded from the list. While there is no reason to suggest that these MPANs have invalid LV feeder or substation connection records, in the absence of location information they cannot be included in network modelling unless the network data explicitly shows the location of the service cable.

MPAN records are also available from the inventory of smart meters on each LV feeder. For around 1% of MPANs, this data indicates a different substation to the records from the CROWN data, and is likely to be more up-to-date.

The following process is used to check the data consistency. This process refers to a 'selected substation', meaning one of the selected substations outlined in the preceding sections of this report; an 'assigned' substation and LV feeder, meaning the connection recorded in CROWN; and 'nearby' substations, meaning a set of substations that are sufficiently close to the selected substation that erroneous connection records might be expected.

Due to the processing time involved, the software does not check the proximity of an MPAN to every other substation and LV feeder. The process summarised below highlights a number of range thresholds that have been tested empirically and specified such that increasing the sensitivity of the proximity analysis would yield very few additional error detections.

Known distribution transformer location

Substations are excluded from the list if the distribution transformer location is unknown. Substations 779997 and 537404 were missing from the records but a location could be determined from the NGED DataPortal2. Where the exact substation location is unknown, an approximate location is determined by calculating the mean location of each of the associated cables and overhead lines in the network data.

Substation 211084 is excluded on this basis.

Feeder branches exist in network data

Substations are excluded from the list if no cable or overhead line branches can be identified in the network data. This requires at least one branch to be present with a circuit id relating to the substation.

Substations 312090 and 218252 are excluded on this basis

MPANs exist at the selected substation

The CROWN database used for this work has no recorded MPANs for substation 779997 so this has been excluded.

Nearby substations

For each selected substation, a set of nearby substations is identified, defined as those with a substation location that is within 1 km of the selected substation. This list of nearby substations is used to set the search scope for feeder branches that may be nearer to the MPAN than the assigned substation. As some LV feeders can be very long, any branch from an identified nearby substation will be searched even if this is further away than the 1 km substation search range.

Where the substation defined in the smart meter inventory differs from the assigned substation, the inventory substation is also added to the list of nearby substations, regardless of the distance between them.

On average, for each selected substation, there around 10 nearby substations identified.

Nearby MPANs

A list of nearby MPANs is created, based on the assigned connection to the list of nearby substations.

Distance from MPANs at a selected substation to their assigned LV feeder

For each MPAN assigned to a selected substation, the analysis software finds the minimum straight-line distance to any cable or overhead line on the assigned LV feeder. This involves iterating through each of the branches on the assigned LV feeder, and through each of the coordinate points that defined the geographical route of the cable.

A distance is also calculated to the nearest point on any other LV feeder connected to the assigned substation. The software records the nearest LV feeder to the MPAN.

Distances from MPANs to LV feeders at nearby substations

If no LV feeder at the selected substation has been found to be within 10 m of the MPAN location, the software then checks distances to all the LV feeders at each of the nearby substations. If any are found to be closer than those at the selected substation, they are recorded as the nearest LV feeder.

Distance from MPANs at nearby substations to their assigned feeders

A similar process is followed for MPANs at nearby substations. The software initially calculates the distance to their assigned feeders. Where selected substations are neighbours, this distance may already have been determined.

As above, distances are calculated to any other LV feeder at the assigned substation

Distances from MPANs at a nearby substation to the selected substation

If the MPAN is more than 10 m distance from any feeder at the assigned substation, the software checks the distance to all the feeders at the selected substation.

Distance from MPANs at a nearby substation to all other nearby substations

If the minimum distance between an MPAN and either its assigned substation or the selected substation is still greater than 200 m, the software checks the distance between the MPAN and all other substations that are defined as nearby the selected substation. This check is intended to avoid re-assigning the MPAN to the selected substation if it happens to be nearer to this than its assigned substation, but where it is still a significant distance from each of them.

7.2 Proximity acceptance criteria for WP1

Results for WP1 and WP2 will inevitably differ due to the increase in accuracy provided by the smart meter data. There is therefore no requirement that the same list of substations be used in each work package.

For the simulation work in WP1, the customer demands are determined based on their estimated annual consumption (EAC) and data is available for each customer individually. The models can therefore connect customers to the nearest LV feeder and any errors in the CROWN database can be corrected. It is also possible for the feeder assigned in CROWN to be correct, even though it may not be the nearest, potentially introducing inaccuracies into the simulation model. However, examples where the connected feeder is not the nearest are relatively rare and so these inaccuracies are unlikely to result in feeder models that are implausible, even though they may differ slightly from reality.

A problem can arise where LV feeders are extended to include new development, particularly as new housing is more likely to have LCTs or smart meters installed and therefore to be found within the set of selected substations. The smart meter inventory includes a number of MPANs that do not yet appear in the CROWN data, and the locations of these connections are therefore unknown. This presents a problem for the simulation model as there is no indication of where on the feeder they should connect.

For WP1, the consistency checks therefore only require that there are no MPANs from the smart meter inventory on a selected LV feeder for which the location is unknown.

Substations are included in the WP1 analysis if all LV feeders at the substation meet the acceptance criteria.

7.3 Proximity acceptance criteria for WP2

The modelling work for WP2 will consider the thermal loading, as recorded in the aggregated demand data, and the headroom available on an LV feeder relative to the smart meter voltage data. For this analysis, it is desirable that the model should include the correct set of customers such that their demand is consistent with the measured voltage data. The concern only applies to MPANs that are included in the aggregated smart meter data, since those that are not can be re-assigned to the nearest feeder, as in WP1.

LV feeders are accepted for the WP2 modelling if

i) there are no MPANs in the smart meter inventory that are assigned to the selected feeder, but which are nearest to another feeder, and
ii) there are no MPANs in the smart meter inventory that are assigned to nearby feeders, but which are nearest and within a distance of 200 m to the selected feeder

As above, substations are included in the WP2 analysis if all LV feeders at the substation meet the acceptance criteria.

7.4 Updated results for WP2

The analysis here has used CROWN data available at the start of the project but revised data for the selected substations has since been obtained. If additional substations are needed for the simulation modelling, or of the proximity acceptance tests are found to be unreliable, the analysis here could be repeated with the revised data.

7.5 Summary of accepted substations

The process above identifies a subset of the initial selection of 195 substations, prioritised for work in WP1 and WP2. It may be possible for further substations to be included in the modelling if revised data can resolve any of the inconsistencies.

	Selected	OLTC	WP1	WP2
• East Midlands	42	0	28	14
• West Midlands	51	2	30	22
• South West	65	2	31	37
• South Wales	37	1	13	13
Total	195	5	102	86

8. Conclusions

This report has reviewed new data from NGED that assesses risks for distribution substations to high proportions of connected generation, long network lengths, and long feeders with a small cross-section area.

The risk assessment data highlights a trend, expected as a consequence of a randomised distribution that smaller substations are more likely to have uptakes of either smart meters or generation that is above a defined threshold. Selection of substations based on having high proportions of smart meters and generation will therefore tend to over-emphasise smaller substations, which are therefore more likely to be pole-mounted. However, it can be argued that these substations are more vulnerable to higher proportions of connected generation, so the sampling bias is appropriate.

A selection method has been proposed, prioritising substations with a high overall risk rating, and also those with high proportions of smart meters. Additional groups are added according to the individual risk factors and these groups are selected separately from substations that are before and after 1980, both pole- and ground-mounted, and from all four regions, to ensure that a wider range of substation type is included.

A total set of 195 substations has been selected for the analysis work in WP1 and for collection of smart meter data to support WP2.

A further set of acceptance tests has been defined to reduce the risk that errors in the CROWN database will reduce the reliability of the results. For WP1, it is required that there are smart meters with unknown locations since this typically indicates additional housing development that cannot be included in the demand model unless the meter locations are known. For WP2, the tests identify feeders where the LV feeder recorded in the CROWN database are inconsistent with the feeder shown in the network data that is closest to the customer location., Feeders are included here when there are no smart meter MPANs that would be either added or removed from the feeder, based on their location and proximity to LV feeder routes.

For WP1, these tests reduce the number of substations to 102, and for WP2 to 86. These numbers may be increased once revised CROWN data is included in the analysis as this will be more concurrent with the smart meter inventory and network data.

A higher than average proportion of the substations with a high overall risk factor is located in the South West region, and this is also reflected in the selected set of substations.

Analysis of the substation risk factor data also suggests that newer transformers tend to have fewer customer connections, but a higher proportion of generators. Unexpectedly, the length of cable with small cross-sectional area also seems to increase with more recent transformer installations.

9. Appendix A – Selected substations

Removed before publication

10. Appendix B – Line codes for cables with small cross-sectional area

10.1 Underground cables

The following underground cable line codes have been categorised as having a small cross-sectional area, and so causing an increased risk of voltage or thermal constraints for downstream customers.

0.003 2c CU
0.003 4c CU
0.0045 2c CU
0.0045 3c CU
0.0045 4c CU
0.007 2c Conc
0.007 2c CU
0.007 3c
0.007 3c CU
0.007 4c CU
0.007 5c CU
0.01 2c Conc
0.01 2c CU
0.01 3c CU
0.01 4c CU
0.01 Conc
0.012 2c Conc
0.012 4c
0.013 2c Conc
0.0145 2c CU
0.0145 3c CU
0.0145 4c
0.0145 4c CU
0.0145 5c CU
0.0145 CU
0.02 2c CU
0.02 3c Conc
0.02 3c CU
0.02 4c Conc
0.02 4c CU
0.02 5c CU
0.02 Conc
0.022 2c CU
0.022 3c CU
0.022 4c CU
0.022/0.012/0.022 DC
0.022/0.012/0.022 VBS
0.0225 2c
0.0225 2c AL
0.0225 2c c/c
0.0225 2c Conc
0.0225 2c Conc DC
0.0225 2c CU
0.0225 3c
0.0225 3c AL
0.0225 3c CU
0.0225 3c CU 11kv AT LV
0.0225 4c
0.0225 4c AL
0.0225 4c CU
0.0225 5c
0.0225 5c AL
0.0225 5c CU
0.0225 Conc
0.023 2c Conc
0.023 3c Conc
0.023 4c
0.025 2c Conc
0.025 2c CU
0.025 3c CU
0.025 4c
0.025 4c CU
0.025 5c CU
0.025 Conc
0.025 CU
0.03 2c CU
0.04 2c AL
0.04 2c Al Conc
0.04 2c c/c
0.04 2c Conc
0.04 2c CU
0.04 3c
0.04 3c AL
0.04 3c Conc
0.04 3c CU
0.04 3c Cu/Cu CNE
0.04 4c
0.04 4c AL
0.04 4c c/c
0.04 4c CU
0.04 5c
0.04 5c AL
0.04 5c CU
0.04 Conc
0.04 CU
0.04/0.04/0.04/0.0225 Cu
0.05 2c
0.05 2c c/c
0.05 2c Conc
0.05 2c CU
0.05 3c
0.05 3c AL
0.05 3c Conc
0.05 3c CU
0.05 3c TCC DC
0.05 3c VBS
0.05 4c
0.05 4c AL
0.05 4c Conc
0.05 4c CU
0.05 5c
0.05 5c AL
0.05 5c CU
0.05 6c CU
0.05 Conc
0.05 CU
0.05/0.022/0.05 VBS
0.05/0.025/0.05 VBS
0.06 2c
0.06 2c AL
0.06 2c c/c
0.06 2c Conc
0.06 2c CU
0.06 2c Cu DC
0.06 3c
0.06 3c AL
0.06 3c Conc
0.06 3c CU
0.06 3c CU 11kv AT LV
0.06 3c Cu/Cu CNE
0.06 4c
0.06 4c AL
0.06 4c Conc
0.06 4c CU
0.06 4c PI VBS
0.06 5c
0.06 5c AL
0.06 5c CU
0.06 6c CU
0.06 Conc
0.06 CU
0.06/0.03/0.06 VBS
0.1 3c
0.1 3c AL
0.1 3c c/c
0.1 3c LTC
0.1 4c
0.1 4c AL
0.1 4c Conc
0.1 5c
0.1 5c AL
0.1/0.035/0.1 VBS
0.1/0.05/0.1 VBS
0.1/0.06 3c
0.1/0.06/0.1 VBS
0.12 4c
0.12 5c
0.125 3c
0.125/0.05/0.125 VBS
0.125/0.06/0.125 VBS
0.145 2c
10 4c CU
16 1ph CNE
16 1ph Cu/Cu CNE
16 1ph Cu/Cu SNE
16 2c
16 2c AL
16 2c CU
16 3c
16 3c c/c
16 3c CNE
16 3c CU
16 3c Cu/Cu CNE
16 3c Cu/Cu SNE
16 3c s/c
16 4c
16 4c AL
16 4c c/c
16 4c CU
16 Al/Al CNE
16 HYB
16 s/c
1c UNKNOWN SIZE
1ph Unknown
2 x 0.0225 1c CU
2 x 0.06 1c CU
25 1ph CNE
25 1ph Cu/Cu CNE
25 1ph Cu/Cu SNE
25 2c
25 2c AL
25 2c c/c
25 2c CU
25 3c
25 3c AL
25 3c Al/Cu CNE
25 3c c/c
25 3c c/c LSF
25 3c CNE
25 3c CON
25 3c Cu/Cu CNE
25 3c Cu/Cu SNE
25 3c HYB
25 3c Hyb LSF
25 3c s/c
25 3c s/c LSF
25 3c SNE LSF
25 3c TR
3 x 0.06 1c Cu DC
3 x 0.075/0.04 1c Cu DC
3 x 0.08/0.05 1c Cu DC
32 3c c/c
35 1ph CNE
35 1ph Cu/Cu CNE
35 1ph Cu/Cu SNE
35 2c
35 2c AL
35 3c
35 3c Al/Cu CNE
35 3c AWC
35 3c AWC LSF
35 3c c/c
35 3c CNE
35 3c CNE LSF
35 3c CON
35 3c Cu/Cu CNE
35 3c Cu/Cu SNE
35 3c Cu/Cu SNE LSF
35 3c HYB
35 3c HYB LSF
35 3c HYB SNE
35 3c s/c
35 3c s/c LSF
35 3c SAC
35 3c SNE LSF
35 3c TR
35 3c WCON
35 3ph AL SNE
35 3ph Al/Cu SNE
35 4c
35 4c AL
35 4c Al/Cu SNE
35 4c CU
35 4c Cu LSF
35 4c DIST
35 4c HYB SNE
35 4c s/c
35 4c SNE LSF
35 Al/Al CNE
35 c/c
35 CON
35 HYB
35 s/c
3c UNKNOWN SIZE
3ph Unknown
4 1ph Cu CNE
4 1ph Cu/Cu CNE
4 1ph Cu/Cu SNE
4 c/c
4 s/c
4 x 0.0225 1c CU
4 x 0.06 1c CU
4c UNKNOWN SIZE
50 3c AWA
50 3c CNE
50 4c
50 4c AL
50 4c CU
5c UNKNOWN SIZE
6 4c CU
7/0.029 2c
7/104 3c
70 3c AWA
70 3c AWC

0.03 3c	0.06/0.04/0.06 CU	25 3c WCON	70 3c CEANDER
0.03 3c CU	0.06/0.06/0.03 Cu	25 4c	70 3c CNE
0.03 3c VBS	0.06/0.06/0.04 Cu	25 4c AL	70 3c CON
0.03 4c CU	0.062 3c	25 4c c/c	70 3c TR
0.03 5c AL	0.075 2c c/c	25 4c CU	70 3c WCON
0.03 5c CU	0.075 2c CU	25 4c Cu LSF	70 4c
0.034 2c c/c	0.075 3c	25 4c WCON LSF	70 4c AL
0.035 2c CU	0.075 3c CU	25 5c c/c	70 4c DIST
0.035 2c DC	0.075 4c CU	25 Al/Al CNE	70 4c WCON
0.035 2c VBS	0.075 5c CU	25 c/c	70 CON
0.035 3c	0.075 CU	25 Hyb	LV Earthwire
0.035 3c CU	0.075/0.035/0.075 DC	25 s/c	LV Unknown from Unattributed
0.035 4c	0.075/0.035/0.075 VBS	2c UNKNOWN SIZE	SV Unknown from Unattributed
0.035 4c CU	0.075/0.05/0.075 VBS	2c VBS	Unknown
0.035/0.012/0.035 VBS	0.097 3c LTC	3 x 0.0225/0.0145 1c Cu DC	UNKNOWN FROM UNATTRIBUTED
0.035/0.022/0.035 VBS	0.1 2c	3 x 0.025/0.0145 1c Cu DC	UNKNOWN SIZE
0.04 1ph Cu/Cu CNE	0.1 2c AL	3 x 0.05/0.025 1c Cu DC	VBS
0.04 2c	0.1 2c c/c	3 x 0.06 1c CU	

10.2 Overhead lines

The following overhead line codes have been categorised has having a small cross-sectional area, and so causing an increased risk of voltage or thermal constraints for downstream customers.

14 Cu PVC	2w 4c 35 ABC	3w 40 AL	4w 4c 35 ABC
16 c/c	2w ABC	3w 4c ABC	4w 4c ABC
16 s/c	2w AL	3w ABC	4w ABC
25 3c c/c	2w ANT	3w AL	4w AL
25 c/c	2w Cu	3w ANT	4w ANT
25 CNE	2w LV Unknown from Unattributed	3w Cu	4w Cu
25 Cu	2w MIDGE	3w MIDGE	4w No.1
25 s/c	2w No.1	3w No.1	4w No1 Cu
2c 35 ABC	2w No.10	3w No1 Cu	4w No1 Cu PBJ
2w 0.02	2w No1 Cu	3w No1 Cu PBJ	4w No1/0 Cu
2w 0.02 AL	2w No1 Cu PBJ	3w No3 Cu	4w No2 Cu
2w 0.02 Cu	2w No2 Cu	3w No4 Cu	4w No2 Cu PBJ
2w 0.02 Cu Bu	2w No3 Cu	3w No4 Cu PBJ	4w No2/0 Cu
2w 0.022 Cu	2w No3 Cu PBJ	3w No6 Cu	4w No3 Cu
2w 0.0225	2w No4 Cu	3w No7 Cu	4w No3 Cu PBJ
2w 0.0225 AL	2w No4 Cu PBJ	3w No7 Cu PBJ	4w No3/0 Cu
2w 0.0225 Cu	2w No5 Cu	3w No8 Cu	4w No4 Cu
2w 0.0225 Cu PBJ	2w No6 Cu	3w Unknown	4w No4 Cu PBJ
2w 0.0225 Cu PBJ HSOS	2w No6 Cu PBJ	3w UNKNOWN FROM UNATTRIBUTED	4w No5 Cu
2w 0.0225 Cu PVC	2w No7 Cu	3w UNKNOWN SIZE	4w No6 Cu
2w 0.025	2w No7 Cu PBJ	3w WASP	4w No6 Cu PBJ
2w 0.025 AL	2w No8 Cu	4c 35 ABC	4w No7 Cu
2w 0.025 AL AL	2w SV Unknown from Unattributed	4w 0.02 AL	4w No7 Cu PBJ
2w 0.025 AL PVC	2w Unknown	4w 0.02 Cu	4w No8 Cu
2w 0.025 Cu	2w UNKNOWN FROM UNATTRIBUTED	4w 0.022 Cu	4w No8 Cu PBJ
2w 0.025 Cu PVC	2w UNKNOWN SIZE	4w 0.0225	4w Unknown
2w 0.03 AL	2w WASP	4w 0.0225 AL	4w UNKNOWN FROM UNATTRIBUTED
2w 0.03 Cu	35 ABC	4w 0.0225 AL PVC	4w UNKNOWN SIZE
2w 0.035	35 c/c	4w 0.0225 Cu	4w WASP
2w 0.04	35 s/c	4w 0.0225 Cu PBJ	5w 0.02
2w 0.04 AL	3w 0.02	4w 0.0225 Cu PBJ HSOS	5w 0.0225
2w 0.04 Cu	3w 0.02 Cu	4w 0.0225 Cu PVC	5w 0.0225 Cu
2w 0.04 Cu Bu	3w 0.0225	4w 0.025	5w 0.025
2w 0.04 Cu PBJ	3w 0.0225 AL	4w 0.025 AL	5w 0.025 Cu
2w 0.04 Cu PBJ HSOS	3w 0.0225 Cu	4w 0.025 AL PVC	5w 0.035
2w 0.04 Cu PVC	3w 0.0225 Cu PBJ	4w 0.025 Cu	5w 0.04
2w 0.046	3w 0.025	4w 0.025 Cu PVC	5w 0.04 Cu
2w 0.046 Cu	3w 0.025 AL	4w 0.03 Cu PVC	5w 16
2w 14 Cu	3w 0.025 AL AL	4w 0.035	5w 16 Cu
2w 14 Cu PVC	3w 0.025 AL PVC	4w 0.04	5w 16 Cu HSOS
2w 16	3w 0.025 Cu	4w 0.04 AL	5w 16 Cu PVC
2w 16 c/c	3w 0.025 Cu Bu	4w 0.04 Cu	5w 32
2w 16 Cu	3w 0.035	4w 0.04 Cu PBJ	5w 35 ABC
2w 16 Cu HSOS	3w 0.04	4w 0.04 Cu PBJ HSOS	5w 3ph UNKNOWN SIZE
2w 16 Cu PVC	3w 0.04 AL	4w 0.04 Cu PVC	5w ANT
2w 16 HDC	3w 0.04 Cu	4w 0.046	5w No1 Cu
2w 16 PVC	3w 0.04 Cu PBJ	4w 0.046 AL	5w No1 Cu PBJ

2w 1ph UNKNOWN SIZE	3w 0.04 Cu PBJ HSOS	4w 14 Cu	5w No2 Cu
2w 22 AL	3w 0.046	4w 16	5w No3 Cu
2w 22 AL HSOS	3w 14 Cu	4w 16 c/c	5w No3/0 Cu
2w 22 Cu HSOS	3w 16	4w 16 Cu	5w No4 Cu
2w 25	3w 16 c/c	4w 16 Cu HSOS	5w No4 Cu PBJ
2w 25 ABC	3w 16 Cu	4w 16 Cu PVC	5w No6 Cu
2w 25 AL	3w 16 Cu HSOS	4w 16 HDC	5w No6 Cu PBJ
2w 25 AL AL	3w 16 Cu PVC	4w 16 PVC	5w No7 Cu
2w 25 AL HSOS	3w 16 HDC	4w 1ph UNKNOWN SIZE	5w Unknown
2w 25 AL PVC	3w 16 PVC	4w 22 AL	5w UNKNOWN FROM UNATTRIBUTED
2w 25 c/c	3w 1ph UNKNOWN SIZE	4w 22 AL HSOS	5w UNKNOWN SIZE
2w 25 CNE	3w 22 AL	4w 22 Cu HSOS	5w WASP
2w 25 Cu	3w 22 AL HSOS	4w 25	6w 3ph UNKNOWN SIZE
2w 25 Cu PVC	3w 22 Cu HSOS	4w 25 3c c/c	6w No1 Cu
2w 25 HDC	3w 25	4w 25 ABC	6w No1 Cu PBJ
2w 25 s/c	3w 25 ABC	4w 25 AL	6w No4 Cu
2w 2c 35 ABC	3w 25 AL	4w 25 AL HSOS	6w No4 Cu PBJ
2w 2c ABC	3w 25 AL PVC	4w 25 AL PVC	6w No8 Cu
2w 32	3w 25 CNE	4w 25 c/c	6w UNKNOWN SIZE
2w 32 AL	3w 25 Cu	4w 25 Cu	7w 0.04 Cu
2w 35 ABC	3w 25 Cu PVC	4w 2c 35 ABC	7w 22 AL
2w 35 AL	3w 32	4w 32	7w 35 ABC
2w 35 Hyb	3w 32 AL	4w 35 ABC	7w UNKNOWN SIZE
2w 35 PVC/PVC	3w 35 ABC	4w 35 AL	Unknown
2w 38	3w 35 AL	4w 38	UNKNOWN FROM UNATTRIBUTED
2w 3ph UNKNOWN SIZE	3w 38	4w 3ph UNKNOWN SIZE	UNKNOWN SIZE
2w 40 AL	3w 3ph UNKNOWN SIZE	4w 40 AL	