ENWL

Voltage Demand Relationship Research

Present, Future Load Modelling and Scenario Analysis

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1. DOCUMENT ISSUE CONTROL

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2. EXECUTIVE SUMMARY

ENWL (Electricity North West Ltd) has a number of voltage control systems operational on its network, with more in development namely the QUEST project. The impacts of the voltage control actions are provided through the loads in the network which exhibit a voltage-demand relationship.

Modelling of this relationship is undertaken by ENWL to determine the operational impact of CLASS (Customer Load Active System Service). However, this modelling could also be used to plan for the benefits and limitations of voltage control applied to its network as part of the QUEST project, at present and in the future.

It is around the point of demand reduction, that can be achieved through voltage control, that OFGEM wish ENWL to highlight possible future changes, via the QUEST project.

In this work, Smart Grid Solutions (SGS) has determined that the prior load models, developed in the previous CLASS study can be improved when coupled with the data sets delivered by CLASS over the last few years, and that these models can be integrated into ENWL electricity network planning models.

When this is coupled with the time-series behaviour of load, and the future magnitude of load growth, it provides a comprehensive understanding of how loads in ENWL's network will behave now and in the future in relation to voltage.

This will ensure any conclusions around the benefits and limitations of any present and future voltage control methodology can be validated via the use of these models.

This document is split into three parts:

Present Loads: Where SGS establish an understanding of the present load modelling ENWL apply.

Future Loads: Where SGS evaluate how future loads are added to the network and the changing behaviour of loads for the following parameters:

- Load Growth Magnitude: How new connections are forecasted
- Load Behaviour Over Time: How load demand is behaving day to day, season to season
- Load Voltage-Demand Relationship: How the instantaneous demand of MW is being modelled by load type and how this will change into the future.

Scenario Analysis: Finally, these outputs are used to create scenario data inputs to the modelling regime used in QUEST to forecast network benefits and limitations for a set of key performance indicators over the future energy scenario period (10 years):

- System Generation/Demand
- System Losses
- Carbon Intensity

The scenario analysis not only answers the question of whether ENWL has considered the voltage-demand relationship changes in their networks, but can update the values associated with this consideration as part of their business case for future control methods to be applied to the network e.g. CLASS only or other QUEST coordinated control methods etc.

Present Loads

The present load section reviews the primary substation loads of the Whitegate Grid Supply Point (GSP) for the purpose of understanding the effect of the voltage-demand relationship they presently express.

This was achieved by reviewing each primary substation's loading information via its historical telemetry to:

- create an exponential load voltage relationship model for every half-hour for each primary substation, and
- determine trends in the load models to identify the strengthening or weakening of the voltage-demand relationship.

Undertaking this work has allowed for:

- Present load models being integrated into network planning models to enable exponential and constant impedance(Z)/current(I)/power(P) (ZIP) model behaviours in order to review the impact of ENWL voltage control systems on demand.
- Identification that, on average, the voltage-demand relationship per primary substation is weakening (less demand change for an associated voltage change), possibly resulting in the reduced benefit of voltage control methods to achieve demand reduction.

The load models created here will improve how load in ENWL networks are modelled and hence how they will behave under voltage control across each half-hour and per season compared to inferring models by mapping to similar behaviours in other studies.

However, these models are derived from a relatively low distribution of available data across the year and, therefore, are limited by the assumptions carried into other half-hour models where measurement data is unavailable. To improve this outcome, the process of event identification was investigated and found to not capture CLASS based voltage reduction events.

Fortunately, since CLASS actions drive data capture, there is higher quality data observed during these operational periods available. When this was investigated for a primary substation, the number of half-hour events where load models could be calculated increased from **12% to 33%,** showing a benefit of ENWL expanding its event detection method, which Fundamentals are now pursuing.

Overall, half-hour event load models can be improved further over time by enriching these data sets by further CLASS and eventually QUEST deployment effecting voltage change operations (transformer tap changing operations) and the subsequent power relationship information that can be derived at these points.

Furthermore, as data sets become richer more advanced modelling techniques can be utilised such as supervised machine learning approaches which may infer more hidden load behavioural relationships embedded in the data.

Part of this report investigates trends in the altering voltage-demand relationship into the future and what it might mean for voltage control methods to extract demand reduction benefits for both the operation of the network and for ENWL's customers.

Future Loads

The future loads analysis utilizes the work undertaken by ENWL's DFES (Distribution Future Energy Scenarios) to identify load magnitude growth scenarios associated with each load category e.g. EV, Domestic Load. Historical records were then used to identify time-series behaviours of these loads. This section then utilises the trend data, showing the changes in voltage-demand per primary substation to configure a load model type to incorporate this relationship change to the future load growth magnitudes. This has achieved a comprehensive view of load growth and its impact to ENWLs network by providing a forecast for:

- Load Magnitude Growth: the total MW growth associated with each primary substation;
- Load Magnitude Behaviour: How this MW demand changes per day and per season, creating a time series profile for each primary substation over the next 30 years, and
- Load Type Changes: Providing a forecast of load type changes to model the MW demand changes due to voltage changes and how this relationship is changing over the next 30 years. Where, based on trend data, the load models can be configured to track these trends as they update year on year.

This will ensure ENWL are forecasting impacts to their network load based on historically referenced behavioural trends rather than trying to predict behaviour as a flat figure by applying a constant assumption of voltage -demand relationship across each primary substation across the next 30 years.

One of the most important observations of this section was that the large transition of load to the electrical network i.e., heat and transport, is presenting itself as voltage independent loads in the network and, therefore, will not be impacted by voltage control methods.

Furthermore, domestic, commercial and industrial loads, thanks to Ecodesign[1] rules will also, more often than not, create voltage independent loads being added to the network. For example, existing fridge freezer, washing machines, with AC motors will all be fully replaced with variable speed drives removing their voltage dependency.

However, there are still voltage dependent loads historically present in the network, and although the magnitude of these loads will reduce over the coming years, for example, the transfer of older AC motors in fridges/dishwashers/washing machines and existing head pumps to variable speed drives, or mains shower conversions removing existing resistive load. Even with these load transfers, voltage dependence is not forecast to completely disappear, due to remaining consumer choice and cost implications, and, therefore, loads will remain that have a voltage controllable demand impact. Having a sensible methodology to trend their impact is required to adequately forecast the benefits and limitations of voltage control methods over the coming years.

The future load outputs are used as inputs to generate scenario data for the final part of the report, presenting the impacts to the network of future load growth, and the effect voltage control will have, considering the future changes to the voltage demand relationship.

Scenario Analysis

The scenario analysis has shown that, under present trends, for the month of January, the average MW demand reduction service for CLASS is 6.47MW by, 2031 this has degraded to 6.17MW, a reduction in service of approximately 5 % by 2031. Although it shows there is still a healthy amount of CLASS demand reduction service provision, this is a not insignificant drop based on current trends. This shows the importance of monitoring network demand trends, if this goes unmonitored and assumed to be flat ENWL could be offering service to the ESO of 95% of this.

Furthermore, the original network was used to investigate the 2031 scenario. At such high growth demand rates much of the network is outside equipment ratings. This made it difficult to model such growth as the model no longer provides convergence under such high levels of demand across existing impedances (voltage collapse). Therefore, the model will have to include reinforcements, when they become necessary to consistently solve the load flow model. This could be coupled with CLASS service provision to show how as a DSO service it could mitigate these required reinforcement works.

[1] https://www.gov.uk/guidance/placing-energy-related-products-on-the-uk-market

To improve the accuracy and precisions of the ZIP models, rather than using the average of the changes applied to all primary substations, each primary substation should be given its unique trend associated with its changing voltage demand relationship. This could be investigated as part of a wider exploratory analysis outside the present scope of this work, where the focus has been on determining the methods of identifying and implementing the changing voltage-demand relationship, rather than establishing the most accurate and precise implementation and optimisation of these novel methodologies.

Finally, the scenario analysis provides ENWL with the tools to identify how the changes to voltage-demand relationship will affect the potential benefit of existing voltage control methods and future methods, as part of QUEST. This work has been fully integrated into the QUEST test bench and satisfies the issues raised by OFGEM that originally triggered the need for this work.

Table 1: Glossary of Terms

Abbreviation	Description
BSP	Bulk Supply Point
CLASS	Customer Load Active System Service
DFES	Distribution Future Energy Scenarios
DNO	Distribution Network Operator
DSO	Distribution System Operator
ENWL	Electricity North West Limited
GSP	Grid Supply Point
HH	Half Hour

3. INTRODUCTION

ENWL has a number of voltage control methods operational on its network, with more in development namely the QUEST project. The impacts of these controls are achieved through the loads in the network which exhibit a voltage-demand relationship.

ENWL's most successful voltage control system is CLASS, this was developed as part of a NIC project in 2014 but has become business as usual. In order to determine the impacts this system would have on the distribution network; the University of Manchester originally undertook an extensive load model analysis of the ENWL network to determine the effects CLASS voltage management would have on demand.

The study relied on inference of load behaviour from various load modelling studies to construct exponential load models[2] and associate them with the CLASS enabled primary substations. This gave a sensible approximation of the effects CLASS would have, as confirmed by the impact CLASS did have, the true measurements taken to confirm this, and the benefits it has provided for ENWL.

To further improve these inferred studies, and to enable ENWL to have confidence in their prediction on CLASS actions and its network effects, the vendor that enables CLASS to be achieved via the SuperTAPP relay, namely Fundamentals, improved the modelling by introducing increased measurement and observations of the primary substation behaviour, allowing for:

1. Taking in-situ measurements of key electrical parameters whenever a transformer tap event occurs at a primary substation.
2. Updating the voltage demand relationship throughout the day by updating the exponential load model when transformer tap events occur in the network.
3. All load types are encapsulated within the voltage-demand relationship.
4. Feeding data to ENWL's historian to enable network studies to be carried out.

The improved data captured by Fundamentals has been greatly beneficial for the operation of CLASS. However, the potential of this data can now be utilised further by using data analytics to formalise the data sets and use exploratory data techniques to determine several important objectives sought by ENWL:

- Creating load models from historical data and map to network planning models to determine the impact of present voltage control methods.
- Identify trends in historic datasets, and project for future trends to determine the state of the voltage-demand relationship for loads in the network, how this might be changing, and what this means for the continued benefits of voltage control methods. ENWL, OFGEM and the wider Distribution Network Operator (DNO)/Distribution System Operator (DSO) community wish to better understand these points.
- Refresh trends periodically to consider the transitory nature of net-zero and impact of global crisis e.g. COVID, Ukraine-Russian conflict impact to gas markets.

This document is split into three parts:

Present Loads: Where SGS establish an understanding of the present load modelling ENWL presently apply.

[2] An Exponential Model is where power demand is not independent of voltage and follows a relationship consistent with an exponential curve, which is dictated by the underlying load structure.

Future Loads: Where SGS evaluate how future loads are added to the network and the changing behaviour of loads for the following parameters:

- Load Growth Magnitude: How new connections are forecasted
- Load Behaviour Over Time: How load demand is behaving day to day, season to season
- Load Voltage-Demand Relationship: How the instantaneous demand of MW is being modelled by load type and how this will change into the future.

Scenario Analysis: Finally, these outputs are used to create scenario data inputs to the modelling regime used in QUEST to forecast network benefits and limitations for a set of key performance indicators over the future energy scenario period of thirty years:

- System Generation/Demand
- System Losses
- Carbon Intensity

Where the scenario analysis not only answers the question of whether ENWL has considered the future voltage-demand relationship changes in their networks, but can update the values associated with this consideration as part of their business case for future control methods to be applied to the network e.g. CLASS only or other QUEST coordinated control methods etc.

The next section investigates the present ENWL loads to baseline the understanding of current assumptions.

4. WHITEGATE GSP PRIMARY SUBSTATION LOADS

The Whitegate Grid Supply Point (GSP) has the following primary substations, split across four Bulk Supply Points (BSPs), some are CLASS enabled sites, and some are not, these distinctions are identified in Table 2. Over the duration of the QUEST project, all substations are scheduled to be upgraded to CLASS if not already upgraded.

Table 2: Whitegate GSP Primaries

BSP	Primary Substation	CLASS Enabled
Chadderton	Langley	Yes
Chadderton	Middleton Junction	Yes
Chadderton	Newton Heath	No
Chadderton	New Moston	Yes
Chadderton	Townley	Yes
Chadderton	Hollinwood	Yes
Chadderton	Chadderton	Yes
Chadderton	Failsworth	Yes
Greenhill	Werneth	No
Greenhill	Waterhead	Yes
Greenhill	St Marys	Yes
Greenhill	Greenhill	No
Greenhill	Belgrave	Yes
Greenhill	Willowbank	Yes
Redbank	Harpurhey	Yes
Redbank	Cannon St	No
Redbank	Blackley	Yes
Redbank	Ancoats T11_T12	No
Redbank	Ancoats T14	No
Royton	Royton	Yes
Royton	Heyside	Yes
Royton	Shaw	Yes

Each of these primary substations will take measurements and upload to ENWL's data historian, for a set of electrical parameters, that informs ENWL how their network was operating. These indicators are average values across each half hour period for:

- Real Power
- Reactive Power
- Phase to Phase Voltage
- Single Phase Current

This data allows ENWL to plan their network for current operational behaviour.

Development at the ENWL primary substations during the CLASS project, namely the introduction of Fundamental's SuperTapp controllers, has enabled enhanced telemetry to be extracted from primary substations where they are deployed, giving more granular measurement of voltage and power, as well as indication of transformer tap positions. This visibility has allowed for more in-depth understanding of the primary substation loading to be achieved via load models.

5. LOAD MODELLING

DNO's plan and operate their network using models of their network to determine compliance with the distribution code. The types of models vary depending on the objective that is required from them, some examples include:

- Electro Magnetic Transient Model (EMT) to analyse such electrical phenomena as switching impacts on the network.
- Real-Time Digital Simulation (RTDS) to analyse electrical parameters such as voltage and current in real time.
- Load Flow Analysis (LF) to analysis electrical parameters such as real and reactive power flows for steady state conditions.

Typically, the more accurate the study, the more computational overhead and burden is associated. Therefore, a modelling type is selected based on what behaviour the DNO wishes to investigate, ensuring that the modelling type can achieve that behaviour.

In this work ENWL wish to make sure their planning of the network considers the voltage-demand relationship effect associated with network loads; therefore, load flow analysis is the type of network analysis that is used to observe behaviour of load under steady-state operational voltage set points.

To achieve the required observations of load behaviour, within load flow analysis, formulation of the network load objects must be adequate to induce a voltage-demand relationship within the load flow study. In this next section this requirement is assessed.

5.1. Loads within Load Flow Analysis

As succinctly put by John Grainger[3]: *"The goal of a power-flow study is to obtain complete voltages angle and magnitude information for each bus in a power system for specified load and generator real power and voltage conditions."*

Once this information is known, real and reactive power flow on each branch as well as generator reactive power output can be analytically determined. Due to the nonlinear nature of this problem, numerical methods are employed to obtain a solution that is within an acceptable tolerance.

However, in order to achieve the solution of these complex problems, simplifications have been made around power demand and frequency. Where frequency is considered static and power demand considered constant for voltage variations.

ENWL's planning models are simulated via load flow as interpreted by the IPSA+ network modelling tool. When we analyse the core functionality of these models it results in load demands set in the model remaining unchanged regardless of the resulting voltage magnitude (constant power) which is not the case on a typical DNO distribution network.

As shown in the example below, changes in voltage at the IPSA+ model secondary bus bar at Heyside primary substation, Figure 1, has no effect on the demand as shown in Figure 2.

[3] Power System Analysis by John Grainger

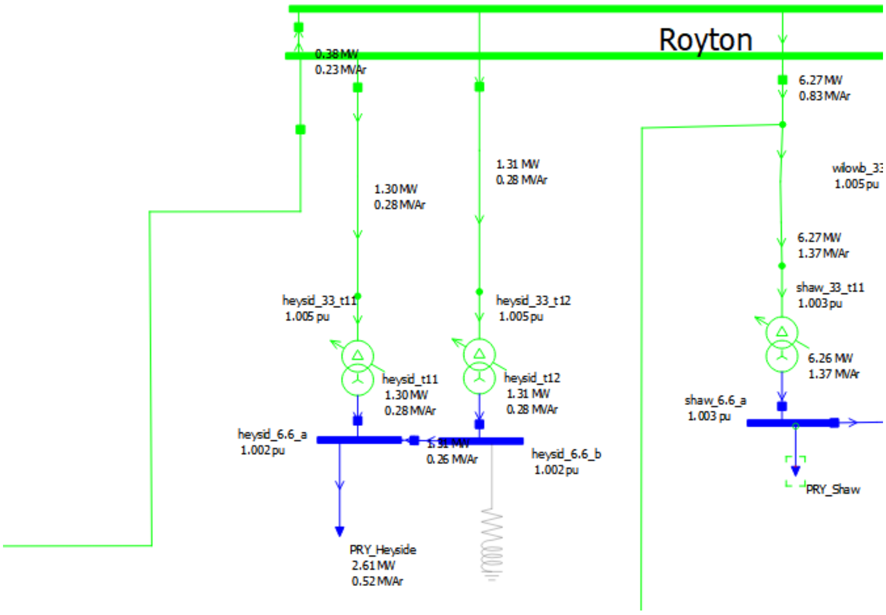

Figure 1: Load Flow with Constant Power Load Objects Nominal voltage set point.

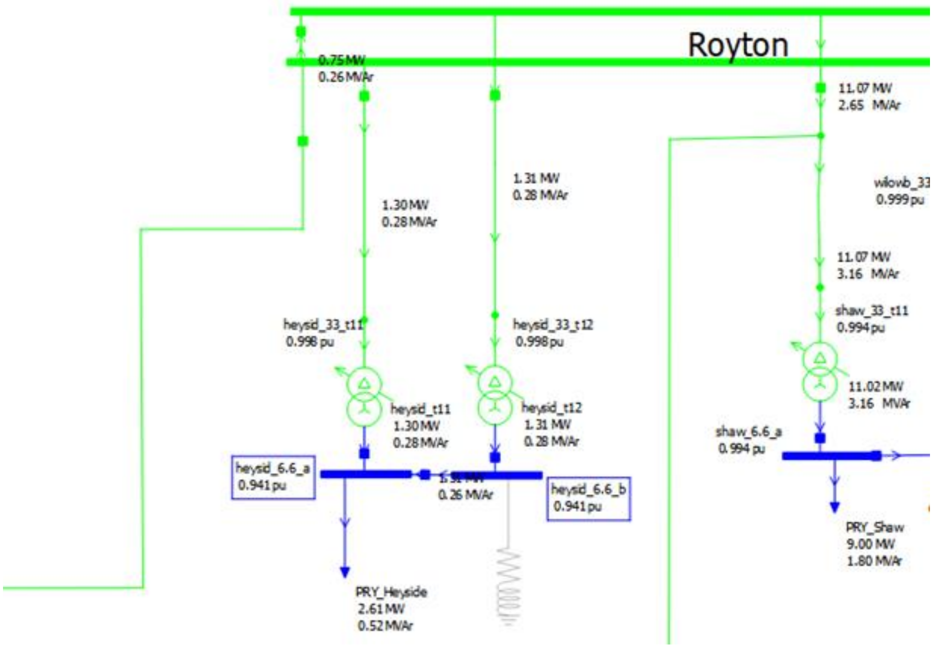

Figure 2: Load Flow with Constant Power Load Objects -6% voltage set point.

This shows that basic load flow analysis delivered by IPSA+ is inadequate for observing the load behaviours ENWL seek (no change in the load at Heyside Primary substation, “PRY_Heyside” in the two figures above). Therefore, the basic load flow model must be extended to include more advanced load models.

5.2. Introducing Load Models into Load Flow analysis.

In the real-world loads are formed of many parts that may exhibit relationships with voltage that are not constant. Therefore, it is important to have the relationships integrated within the analysis of the network, otherwise import behaviour may be ignored, resulting in conservative or optimistic conclusions about the planning or operation of the electricity network.

There are three main load type characteristics of interest in a power system: constant impedance (Z), constant current (I) and constant Power (P). These are illustrated in Figure 3.

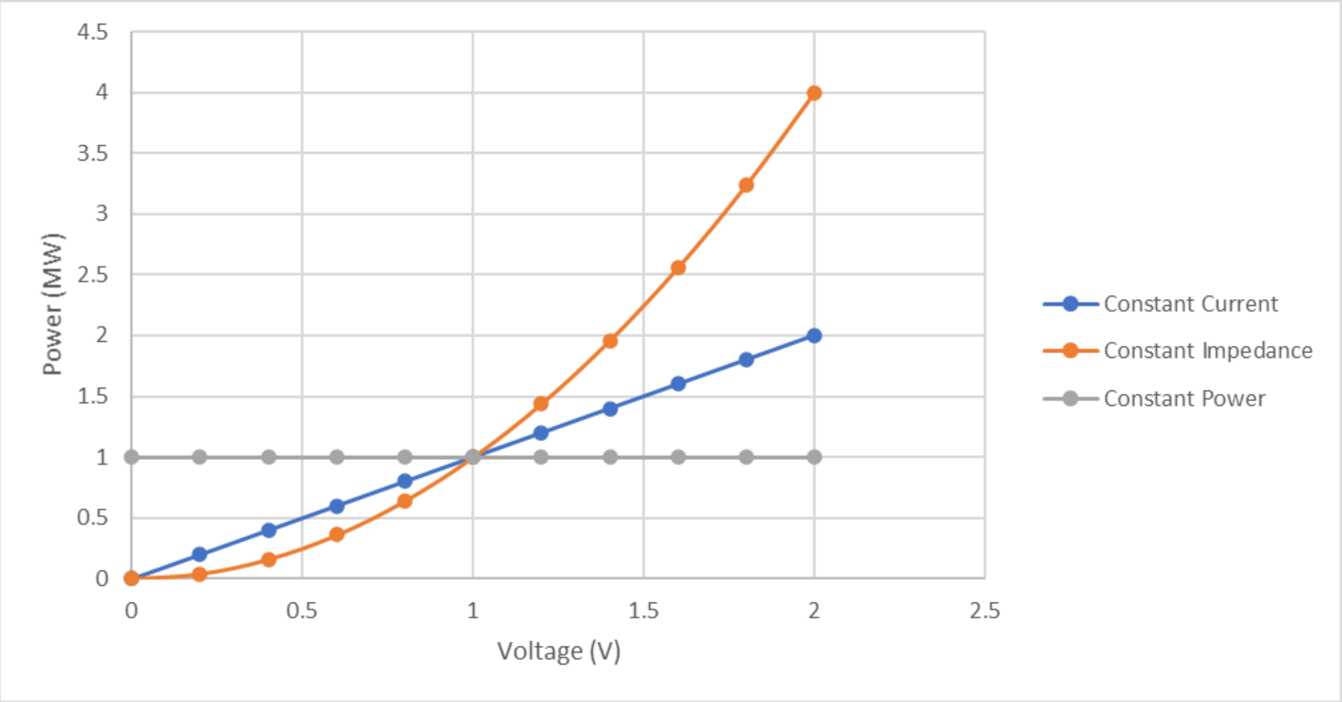

Figure 3: Load Type Characteristics and their Voltage-Demand relationship

As shown, for two of these load characteristics (constant impedance, constant current), as voltage changes so does their power demand, therefore, they are voltage dependent.

One way to introduce the voltage-demand relationship effect into network modelling is to introduce loads as objects within the load flow equation that do exhibit voltage-demand relationship.

In the example shown here, modelling a load as a shunt branch is applied to the model, calculating the shunt resistance, reactance, and susceptance values to mimic a constant impedance square law relationship highlighted by the orange trend in Figure 3.

Now when voltage changes, at the node to which the load is connected, the demand alters.

This is shown in Figure 4. Reducing from 2.61MW (Figure 2, Figure 4) to 2.41MW with the model network voltage reduced by approximately 6%.

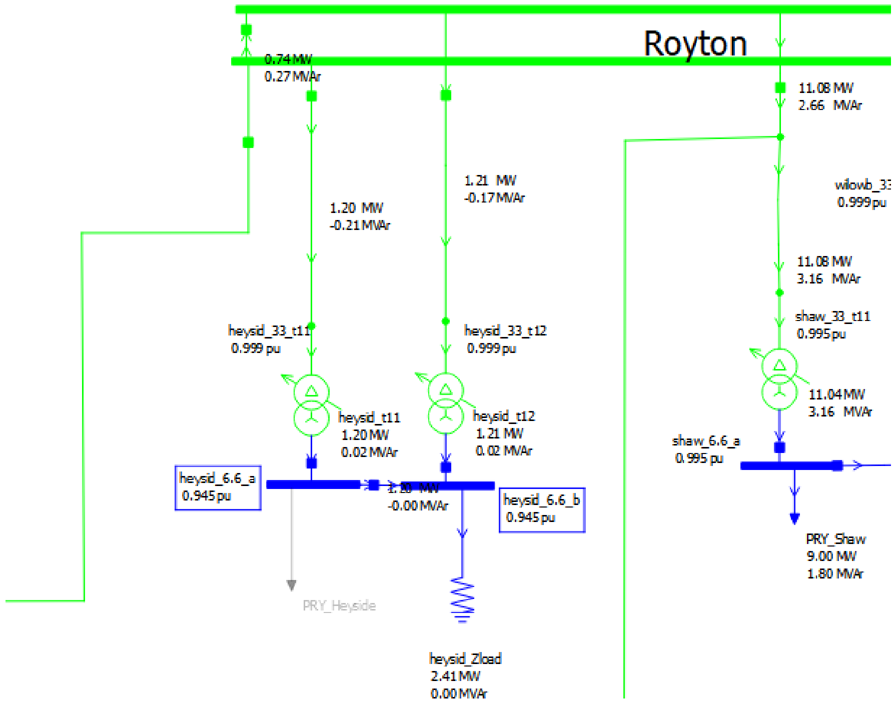

Figure 4: Load Flow with Constant Impedance Load Objects 6% voltage set point.

However, this constant impedance model is not entirely accurate in terms of the behaviour of ENWL's network demands. In the original CLASS project, and in order to predict the behaviour of loads under CLASS action, ENWL has modelled loads as an exponential model.

$$P_{EXP} = P_b \cdot (\frac{v}{v_b})^{K_p}$$

This encapsulates load behaviours into a single function, determined by the Kp value, where:

- Kp=2 results in behaviour of a constant impedance load (Orange trend in Figure 3)
- Kp=1 results in behaviour of a constant current load (Blue trend in Figure 3)
- Kp=0 results in behaviour of a constant power load (Grey trend in Figure 3)

And Kp values in-between provide a mix of load effects.

Another load model type is a ZIP model approach which identifies each constituent part of the relationship shown in Figure 3:

$$P_{ZIP} = P_b \cdot \left[K_Z \cdot \left(\frac{v}{v_b}\right)^2 + K_I \cdot \left(\frac{v}{v_b}\right) \quad + K_p\right]$$

$$K_Z + K_I + K_p = 1$$

Where K_Z , K_I and K_p are the proportion of load modelled as constant impedance, constant current and constant power.

Both load model types provide a more representative behaviour of loads in relation to voltage and are beneficial to have incorporated into planning models to determine the effect voltage control will have on the network power flows.

5.3. External Load Models within Load Flow Analysis

ENWL employ the IPSA+ electricity network modelling tool for their network planning.

IPSA+ base load flow functionality is limited to the introduction of constant impedance models for voltage demand relationships.

IPSA+ can include exponential load models and ZIP models as a plugin (not a part of base load flow functionality), but that is not adequate, as access to plugin set points as part of the python API may limit the future analysis required from time-series analysis; where time-series analysis is critical in assessing how load behaviour changes at different times of the day and during different periods of the year.

Therefore, having externally applied load model capabilities implemented as a python function, enables a load to be expressed as an exponential model or ZIP model and its affects can be used as part of ENWL's IPSA+ planning models integrated into time series analysis.

This is implemented using the following algorithm.

1. The base historical real demand is set within the load flow model and solved;
2. The resulting voltage (v) and base real power demand (P_b) and the base voltage (v_b) assumed to be 1 p.u. if no historical measurement data is available, is used as part of the exponential load model calculation as expressed:

$$P_{EXP} = P_b \cdot (\frac{v}{v_b})^{K_p}$$

3. The resulting demand (P_{EXP}) is then applied to the load flow model and the model re-solved.

A validation example is given, where we can use the exponential model to express the same relationship as a constant impedance load, by setting Kp to 2.

K_p=2, V_b = 1 and P_b=2.7

With this set we run a load flow resulting in a voltage at v=0.951 at the Heyside secondary busbar with the load unchanged.

$$P_{EXP}=2.70*(0.951/1.00)^2$$

$$P_{EXP}=2.44MW$$

The load model predicts a demand of 2.44MW as a result of the voltage change, this is confirmed by applying the voltage change to the constant impedance model in IPSA+ and the resulting load flow results illustrated in Figure 5.

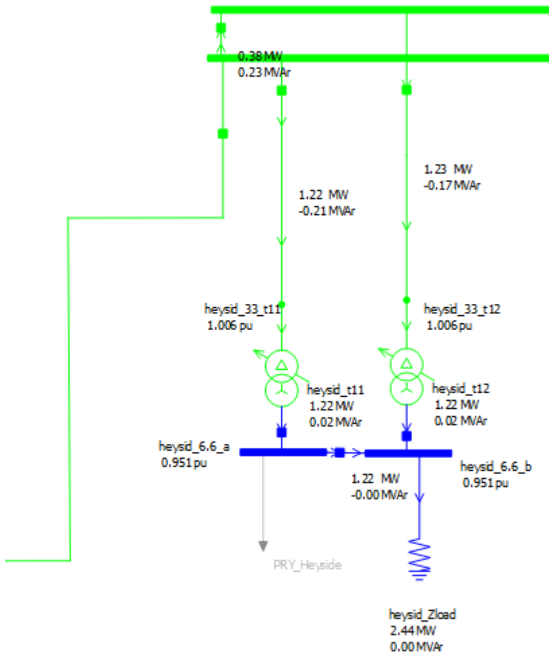

Figure 5: Load flow with constant impedance internally modelled

The external load model is therefore adequate to apply demands as an external input to update the load flow solution. This enables two important outcomes:

- The external load models can be updated via a python API and applied to ENWL's planning models as part of a time-series analysis
- Voltage-demand relationship effects on the network models can be analysed, which will satisfy the requirement to show the behaviour voltage control methods have on the network, and the possible benefits and limitations this may achieve to the planning and operation of the network.

With this functionality enabled, creating exponential models for the Whitegate GSP is now required to use as part of this network modelling functionality and to enable exploratory data analysis of demand change due to voltage control methods.

6. LOAD MODELLING FOR WHITEGATE GSP

Each primary substation in the Whitegate GSP, that has been an active CLASS site, has an enhanced data set associated with it, as provided by the Fundamentals' SuperTAPP relays. A part of this data set is a calculation of the primary substation's voltage-demand relationship, expressed as the K_p value, calculated using analogue measurement data for every significant transformer tap change at the primary substation.

Due to the increased frequency in operation of the tap for enhanced voltage control purposes, it has allowed for K_p values to be calculated at a multitude of times in the year. This means a distribution of K_p values across a year can be created, versus a single constant K_p model which may reduce the visibility of the underlying load structure changes with time.

6.1. Exponential Load Modelling for Whitegate GSP

For each CLASS primary substation, when a natural change in tap occurs due to loading conditions, the measured data and following formula is used to calculate the K_p value using the following equation:

$$K_p = log_{10}(\frac{P_{EXP}}{P_b})/log_{10}(\frac{v}{v_b})$$

where:

- v, P_{EXP}, are measurements after tap has finished,
- v_b, P_b are measurements before the tap has started.

Fundamentals apply data correcting methods to avoid transient effects, specifically a geometric averaging protocol.

It is assumed that this approach results in a relatively accurate calculation of K_p at the instant of tap change and using the raw measurement data to recalculate K_p values using alternate methods would not result in an improved level of accuracy, beyond what is already provided by the K_p values within the data set.

To make the K_p data more compatible as an input data set regarding applied data analytics, the non-uniform time series data sets are re-sampled and averaged over a half-hour window, this is then stored by ENWL in a historian. This provides two benefits:

- data is smoothed to provide a stable load behaviour for a set half hour period;
- K_p values can be linked to the historical half hour data sets.

With these assumptions applied, the average half-hour power flow can be used as the base power (Pb) and the average half-hour voltage can be used as base Voltage (v_b) to create an exponential load model for the primary substation per half hour.

6.2. Investigation of K_p Values

The K_p values determine how a load demand will change for changes in underlying load structure, for each season, across the year and in load structure changes year on year. The calculated K_p values derived from real time measurement for primary substations within the Whitegate GSP have been analysed to:

- Determine the coverage of Kp data across time to provide insight into how useful the data set is, and

- Determine how the K_p data may be changing due to the underlying load or load behaviours altering in the downstream networks.

Both these points are discussed in the next sections.

6.2.1. K_p Voltage-Demand Relationship Temporal Coverage

The frequency distribution of the K_p value across the year will determine the quality of the data set, the more data coverage, the higher the quality.

For most primary substations, a two-year data set is available for analysis.

Frequency Distribution: Half-Hourly

Every daily half-hour across the two-year period was grouped, where they exist, and tabulated to show how many K_p values have been calculated across the time period, see Table 3.

Table 3: K_p Values Per Half-Hour Group Across Two Year Period (Hollinnwood)

Time	ENWL
0:00	16
0:30	0
1:00	24
1:30	38
2:00	0
2:30	19
3:00	15
3:30	0
4:00	18
4:30	22
5:00	0
5:30	68
6:00	79
6:30	0
7:00	66
7:30	40
8:00	0
8:30	28
9:00	29
9:30	0
10:00	31
10:30	23
11:00	0
11:30	23
12:00	16
12:30	0
13:00	22
13:30	25

Time	ENWL
14:00	0
14:30	24
15:00	36
15:30	0
16:00	32
16:30	28
17:00	0
17:30	34
18:00	32
18:30	0
19:00	36
19:30	26
20:00	0
20:30	51
21:00	51
21:30	0
22:00	37
22:30	40
23:00	0
23:30	18
Total Percentage Coverage	12%

These figures in the table are presented graphically in Figure 6.

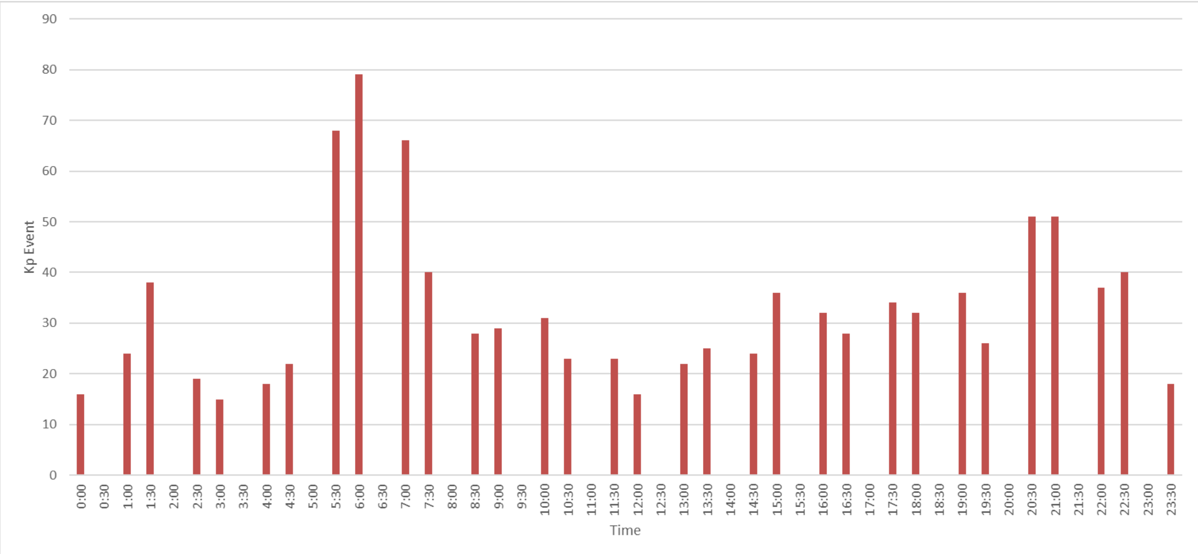

Figure 6: Summation of Event Detection per Half-Hour across a year

The frequency distribution shows that at least one K_p event, per half hour, has been captured for 12% of every half hour in the year.

Frequency Distribution: Monthly

Table 4 shows the frequency distribution of K_p data from each half-hour, per month.

Table 4: K_p Values Per Month Group Across Two Year Period (Hollinwood)

Row Labels	Sum of ENWL
January	134
February	140
March	58
April	0
May	0
June	88
July	107
August	117
September	111
October	80
November	98
December	114

The hourly and monthly distribution of K_p values is not large, resulting in a low data quality.

Kp values are only calculated in the historian when a single tap action occurs on a pair of substation transformers, due to natural loading conditions, and not due to a tap action across both transformers in the pairs due to CLASS actions.

If the Kp value was calculated on every tap action including both transformers in a pair and multiple tap step changes, there would be an expectation of a higher number of taps during high demand periods (CLASS operational period).

To improve the data quality SGS recalculated the events based on the same raw data that ENWL use as an input to their historian, but applying a more extensive event detection process.

6.3. Kp Historian Analysis

ENWL provided SGS with the raw second by second relay data associated with a transformer pair at Hollinwood BSP across a year, as well as the Kp data from the historian across the same period.

The SGS method for event detection is:

- When any tap change occurs, on either transformer in a pair, prior to the previous second, an event start is recorded and the current and voltage of the time step recorded at this point.
- A watchdog timer is started, monitoring tap events across each transformer pair, including multiple events, once no tap change has been detected on either transformer for 30 seconds, the event is considered cleared, and a measurement is taken at the end of this settled period.
- A Kp value is then calculated using the data associated with the start and end of the event.

This method resolves the previous under reporting of tap events.

The post analysis information is compared against the original ENWL historian Kp information.

Table 5: K_p Values Per Half-Hour Group Across Two Year Period SGS Method (Hollinnwood)

Time	ENWL	SGS
0:00	16	56
0:30	0	0
1:00	24	51
1:30	38	47
2:00	0	0
2:30	19	56
3:00	15	39
3:30	0	0
4:00	18	55
4:30	22	45
5:00	0	0
5:30	68	99
6:00	79	172
6:30	0	0
7:00	66	143
7:30	40	126
8:00	0	0
8:30	28	119
9:00	29	115
9:30	0	0
10:00	31	100
10:30	23	72
11:00	0	0
11:30	23	72
12:00	16	80
12:30	0	0
13:00	22	69
13:30	25	53
14:00	0	0
14:30	24	80
15:00	36	68
15:30	0	0
16:00	32	124
16:30	28	128
17:00	0	0
17:30	34	120
18:00	32	95
18:30	0	0
19:00	36	99
19:30	26	101
20:00	0	0

Time	ENWL	SGS
20:30	51	111
21:00	51	106
21:30	0	0
22:00	37	107
22:30	40	117
23:00	0	0
23:30	18	68
Total Percentage Coverage	12%	33%

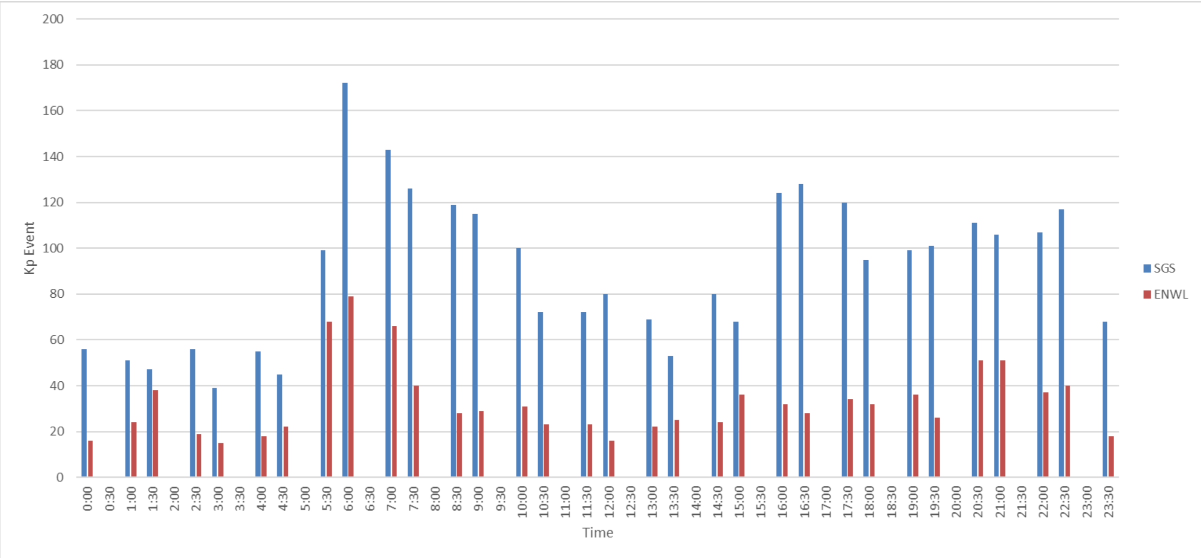

Figure 7: Summation of Event Detection per Half-Hour across a year

Increasing the event detection almost triples the coverage of events, enriching the data set as shown in Figure 7.

With the distribution covering at least a third of the year this should allow for insight to be derived on the behaviour of the load in terms of:

- how the voltage demand relationship alters from day to day;
- how the voltage demand relationship alters from season to season.

These behaviours are investigated in the next section.

6.3.1. K_p Voltage-Demand Relationship Strength Methodology:

This methodology determines how the strength of the Voltage-Demand relationship can be expressed for a data set; this allows comparison of other years to determine how the relationship is changing.

1. The half-hour K_p values are sorted from min to max for a year resulting in a loading curve
2. These values are grouped into their load type relationships effectively a ZIP representation:
    a. Constant Power (P)<0.5
    b. Constant Power-Constant Current (PI) >0.5 <1
    c. Constant Current- Constant Impedance (IZ) >1 <1.5
    d. Constant Impedance (Z) >1.5
3. The constant power and constant current values (values below 1) are summated to represent a weak voltage demand relationship group, and the constant current and constant impedance values (values above 1) are summated to represent a strong voltage demand relationship group.
4. Finally, the groups are presented as percentages representing the persistence of a weak or strong voltage demand relationship across the period of the year. Where changes in this relationship indicate a strengthening or weaking of the relationship between voltage and demand in general terms.

An example is given for Hollinnwood primary substation which is part of Chadderton BSP network:

Step 1:

The K_p results, in the historian data for each time step are sorted, from min to max, for each year to create a load curve relating to K_p values as shown in Figure 8.

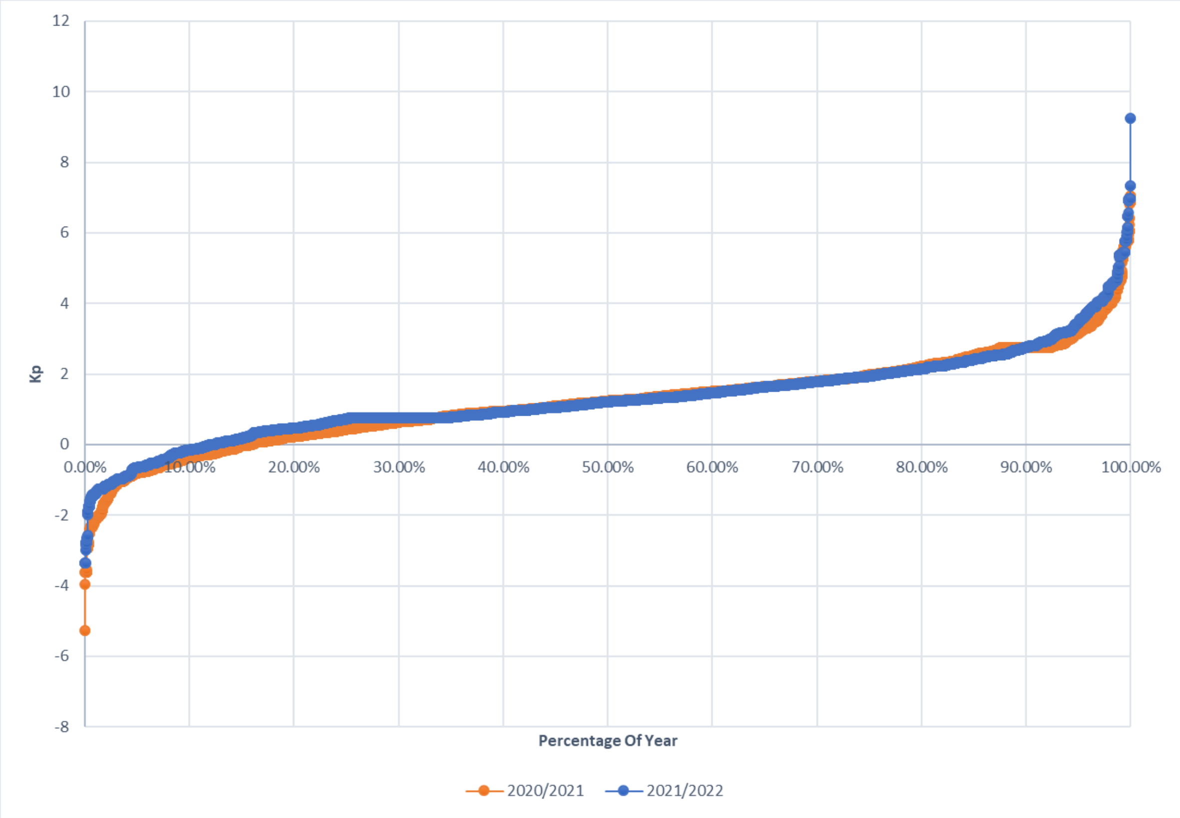

Figure 8: Load Curve expressed as Kp value

Step 2 and 3:

The Kp values that form the loading curve are then grouped into the load types, which determine the strength of the voltage demand relationship they exhibit, where values associated <1 exhibit a Weaker Voltage Demand Relationship (VDR) and >1 exhibit a Stronger VDR. The is summarised in Table 6 for Hollinwood primary substation.

Table 6: Tabulation of Kp Data for Hollinwood Primary

Relationship	Load Type	Kp Range	Time Steps	Percentage Of Year	Sum Of Periods	Time Steps	Percentage Of Year	Sum Of Periods
Weaker VDR	Constant Power (P)	Values <0	3677	20.99%	7566	4684	26.74%	7340
	Constant Power/Constant Current (PI)	Values >0 <1	3889	22.20%		2656	15.16%	
Stronger VDR	Constant Current/Constant Impedance (IZ)	Values >1 <2	3116	17.79%	9954	3165	18.07%	10180
	Constant Impedance (Z)	Values >2	6838	39.03%		7015	40.04%	

Step 4:

Finally, the periods summated to represent a weaker and stronger relationship between voltage and demand are presented as a percentage in order to more clearly show the change in the relationship. These results are tabulated in Table 7

Table 7: Voltage-Demand relationship changes across years (Hollinwood)

	Periods with WVDR	Periods with SVDR	Number Of Periods
2020/2021	7566	9954	17520
2021/2022	7340	10180	17520
2020/2021	43.18%	56.82%	
2021/2022	41.89%	58.11%	
Change	-1.29%	1.29%	

The results for Hollinwood primary substation show that periods representative of a weaker voltage-demand 7566 relationship have decreased to 7340 between the two years by -1.29% and, an equal increase in periods representative of a stronger voltage-demand relationship. A negative change in the weaker VDR instances and a positive change in the stronger VDR instances indicates a strengthening of the voltage-demand relationship and, therefore, an increase of impact from voltage control methods applied to this primary substation.

Conversely, comparing another primary substation in the BSP, New Moston, shows the reversal of this relationship:

Table 8: Voltage-Demand relationship changes across years (New Moston)

	Periods with WVDR	Periods with SVDR	Number Of Periods
2020/2021	4722	12798	17520
2021/2022	5743	11777	17520
2020/2021	26.95%	73.05%	
2021/2022	32.78%	67.22%	
Change	5.83%	-5.83%	

Where Table 8: Voltage-Demand relationship changes across years (New Moston) the voltage-demand relationship is weakening, since in year 1 there are 4722 half hour periods that exhibit a weak relationship and this has increased to 5743 the next, a change of 5.83% across the whole data set.

To determine the conclusiveness of this relationship, the entire Whitegate GSP was analysed for years 2020/2021 and 2021/2022 and the change in the strength of VDR results are tabulated in Table 9. At primary substations where CLASS has not been applied, no Kp calculations can be performed and are assigned N/A.

Table 9: Change in Voltage-Demand Relationship for Whitegate GSP Primaries

BSP	Pry	% Change
Chadderton	Langley	13.19
Chadderton	Middleton Junction	-0.53
Chadderton	Newton Heath	N/A
Chadderton	New Moston	5.83
Chadderton	Townley	10.79
Chadderton	Hollinwood	-1.29
Chadderton	Chadderton	-0.78
Chadderton	Failsworth	45.90
Greenhill	Werneth	N/A

BSP	Pry	% Change
Greenhill	Waterhead	6.27
Greenhill	St Marys	-7.85
Greenhill	Greenhill	N/A
Greenhill	Belgrave	7.59
Greenhill	Willowbank	6.27
Redbank	Harpurhey	1.73
Redbank	Cannon St	N/A
Redbank	Blackley	4.77
Redbank	Ancoats T11_T12	N/A
Redbank	Ancoats T14	N/A
Royton	Royton	-2.09
Royton	Heyside	-6.99
Royton	Shaw	-1.73
Average		~5%

Note that in Table 9 a positive percentage change relates to an increase in the weaker VDR instances and a decrease in the stronger VDR instances i.e. a weakening of the VDR relationship.

- Since the weakening of the voltage=demand relationship is seen as a worse outcome for voltage control methods it is highlighted in red.
- Since the strengthening of the voltage=demand relationship is seen as a better outcome for voltage control methods it is highlighted in green.

A negative percentage change relates to a decrease in the weaker VDR instances and an increase in the stronger VDR instances i.e. a strengthening of the VDR relationship.

Note that the change in Voltage-Demand Relationship for Whitegate GSP Primaries can't be fully populated until ENWL can provide data for the non-CLASS enabled substations in Table 9.

The table shows that there are more primary substations where there is a weakening of the voltage demand relationship since nine substations show a reduction in Kp value versus seven that have shown an increase.

Therefore, a reduction in impact from voltage control methods. However, some BSP groups contain primary substations that show a strengthening of the relationship, or a steadying of this relationship (no change greater than 1%). This highlights that the voltage-demand relationship is not just a fit and forget relationship, there is clearly changes occurring in the network demand.

Therefore, when modelling for future operational impacts:

- The present voltage demand relationship may not be the same moving into the future, on average the relationship does appear to be weakening.
- However, this relationship is primary substation dependent, furthermore
- The relationship changes should be monitored year on year to determine whether an equilibrium has been achieved.

Any future modelling could use trends associated with these findings to incorporate impacts to voltage controlled demand methodologies in order to improve accuracy of the business cases built around the modelling.

7. PRESENT LOAD CONCLUSIONS

ENWL understood the importance of load models to determine the impact of voltage control methods on their network at the inception of the CLASS development. However, the data sets were limited, and, therefore, these impacts could only be approximated through inferring behaviour from comparative network studies.

Over the past few years, the collection of data from their CLASS enabled sites has allowed for the load models to be revisited, and the limitations of the previous models improved.

The data provided from CLASS enabled primary substations allows for the creation of load models that has enabled the introduction of more representative voltage-demand relationships into network modelling analysis. This will allow ENWL to :

- more accurately determine the effects of voltage control methods upon their network in relation to demand per-half hour across the year, and
- determine, from trends in this data, how the strength of this relationship is changing.

The first point will allow ENWL to determine how the introduction of further voltage control methodologies, namely QUEST, will affect the network operation, and how CLASS will continue to affect the network, before QUEST delivery.

The second point will allow ENWL to determine how development of the network in the future may affect the impact of voltage control methodologies. This will be key to highlighting the benefits and limitations of developments to both the operation of the network and for the customers connected.

The next deliverable will focus primarily on the second point. Investigating whether the exponential model alone is accurate to apply to network models, considering the trends shown in the present models, these are pointing towards a direction of travel for demand characteristics to a more constant power-constant current future.

8. FUTURE LOAD MODELS

Integrating load growth within the electrical network will impact the existing network capacity headroom. Therefore, understanding how flexible the load growth will be is important to ENWL for determining their reinforcement planning and also how they can plan services around flexibility.

To understand the impact, load growth can be split in to three parts:

- Load magnitude growth: The MW connection growth
- Load magnitude behaviour: How the MW demand changes according to different behaviour cycles across day and night, holiday, and seasonal periods.
- Load Type Changes: The instantaneous MW changes effected by voltage change.

To understand these parts, ENWL's Distribution Future Energy Scenarios (DFES) work was investigated. This gives multiple scenarios for potential growth linked to the demand magnitude.

8.1. Load Magnitude Growth

In the DFES workbook[4], multiple types of load growth categories have been identified, which are:

- DCI Demand: Domestic, Commercial, and industrial (DCI) sites (excluding heavy industry connected at higher voltage)
- Electric Vehicle Demand: The uptake of Electric Vehicles and their domestic chargers (Transportation to Electrical Network)
- Heat-Pump: The uptake of Heat Pumps and their installed capacities (Heat to Electrical Network)

Where the electrification of heat and transport magnitudes are so large, relative to typical growth, they have been decoupled from general domestic, industrial and commercial load growth. The growth of each area will super impose to create the total maximum demand forecasted at each primary substation.

8.1.1. Embedded Load Growth

The embedded load growth forecasts from the DFES are presented in the following tables and figures. Where the tables show how much growth is forecast relative to the 2021 demand, for example in Table 10, Langley primary substation by 2051 has added 7.88MW on top of the existing demand in the network: 3.78MW between 2022- 2031, 2.76MW between 2031-2041, and 1.34MW between 2041-2051. This total growth is shown per period and stacked per primary substation in the graph in Figure 9. Two scenarios are chosen for investigation here based on the DFES Steady Progression and Consumer Transformation.

Table 10 - Maximum DCI Demand (MW) Growth Using Steady Progression Forecast

BSP	Primary Substation	2031	2041	2051
Chadderton	Langley	3.78	2.76	1.34
Chadderton	Middleton Junction	3.28	2.47	1.31
Chadderton	Newton Heath	2.26	1.55	0.67
Chadderton	New Moston	3.35	3.16	1.65

[4] https://www.enwl.co.uk/get-connected/network-information/dfes/ : 2021 Version uploaded 13th January 2022

BSP	Primary Substation	2031	2041	2051
Chadderton	Townley	2.39	1.46	0.38
Chadderton	Hollinwood	2.27	1.37	0.53
Chadderton	Chadderton	3.21	1.67	1.27
Chadderton	Failsworth	2.82	1.95	0.83
Greenhill	Werneth	2.37	1.73	0.65
Greenhill	Waterhead	2.05	1.48	0.66
Greenhill	St Marys	2.80	0.95	0.65
Greenhill	Greenhill	6.85	3.21	1.46
Greenhill	Belgrave	2.02	1.59	0.71
Greenhill	Willowbank	3.25	2.04	1.24
Redbank	Harpurhey	5.03	2.73	1.13
Redbank	Cannon St	10.54	0.94	-0.14
Redbank	Blackley	2.92	2.44	1.10
Redbank	Ancoats T11_T12	4.34	1.07	0.74
Redbank	Ancoats T14	8.38	0.46	0.16
Royton	Royton	2.89	1.90	0.80
Royton	Heyside	1.88	1.80	1.31
Royton	Shaw	2.95	2.39	1.14

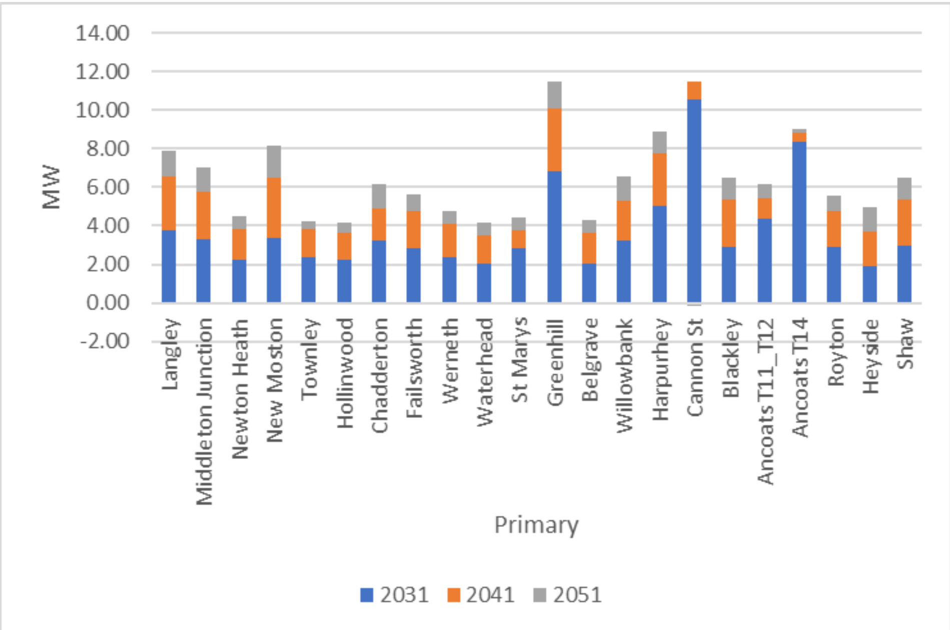

Figure 9: Primary Substation DCI Demand Growth (Steady Progression)

The Consumer Transformation forecast, Table 11, shows a higher growth rate, see also Figure 10.

Table 11 - Maximum DCI Demand (MW) Using Consumer Transformation Forecast

BSP	Primary Substation	2031	2041	2051
Chadderton	Langley	4.65	9.10	8.47
Chadderton	Middleton Junction	3.79	7.65	7.30

BSP	Primary Substation	2031	2041	2051
Chadderton	Newton Heath	2.84	5.17	4.66
Chadderton	New Moston	3.81	7.67	5.85
Chadderton	Townley	1.87	3.27	2.77
Chadderton	Hollinwood	2.55	4.25	3.99
Chadderton	Chadderton	3.52	6.55	6.72
Chadderton	Failsworth	2.83	7.18	6.92
Greenhill	Werneth	2.28	5.57	4.86
Greenhill	Waterhead	2.14	5.70	5.23
Greenhill	St Marys	2.75	2.31	1.86
Greenhill	Greenhill	6.80	10.40	8.87
Greenhill	Belgrave	2.20	5.92	5.49
Greenhill	Willowbank	3.72	7.07	6.18
Redbank	Harpurhey	5.38	8.31	7.44
Redbank	Cannon St	9.42	2.04	1.50
Redbank	Blackley	3.47	6.19	4.85
Redbank	Ancoats T11_T12	4.20	4.79	4.39
Redbank	Ancoats T14	6.87	1.02	0.75
Royton	Royton	3.08	7.48	7.11
Royton	Heyside	2.39	6.52	6.07
Royton	Shaw	2.89	8.56	7.88

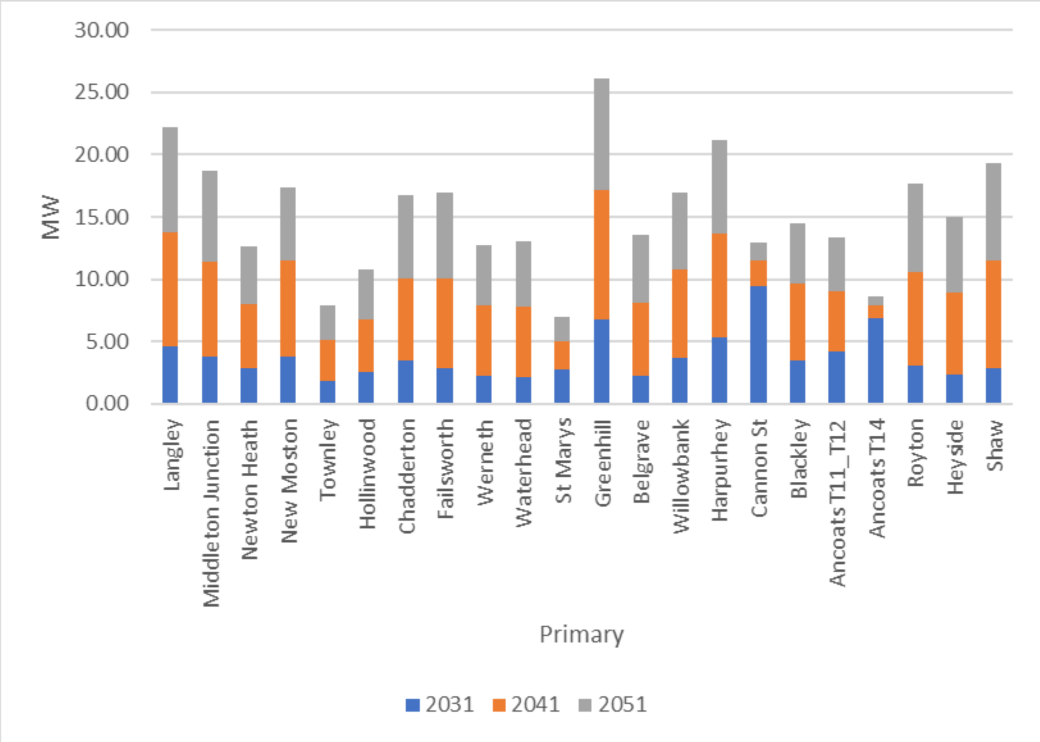

Figure 10: Primary Substation DCI Demand Growth (Consumer Transformation)

The EV DFES data identifies uptake in electric vehicle numbers per primary substation, it is then assumed a charger of 7kW is applied to satisfy the LV demand of the vehicle. This is presented in Table 12 and shown graphically in Figure 11.

Table 12 - EV Uptake Using Steady Progression Forecast (MW)

BSP	Primary Substation	2031	2041	2051
Chadderton	Langley	21	18	5
Chadderton	Middleton Junction	21	18	5
Chadderton	Newton Heath	12	10	3
Chadderton	New Moston	25	21	6
Chadderton	Townley	17	14	4
Chadderton	Hollinwood	14	12	3
Chadderton	Chadderton	21	18	5
Chadderton	Failsworth	18	15	4
Greenhill	Werneth	18	15	4
Greenhill	Waterhead	15	13	4
Greenhill	St Marys	4	3	1
Greenhill	Greenhill	26	22	6
Greenhill	Belgrave	16	14	4
Greenhill	Willowbank	14	12	3
Redbank	Harpurhey	21	18	5
Redbank	Cannon St	1	1	0
Redbank	Blackley	22	19	5
Redbank	Ancoats T11_T12	6	4	1

BSP	Primary Substation	2031	2041	2051
Redbank	Ancoats T14	1	1	0
Royton	Royton	20	17	5
Royton	Heyside	14	12	3
Royton	Shaw	28	23	7

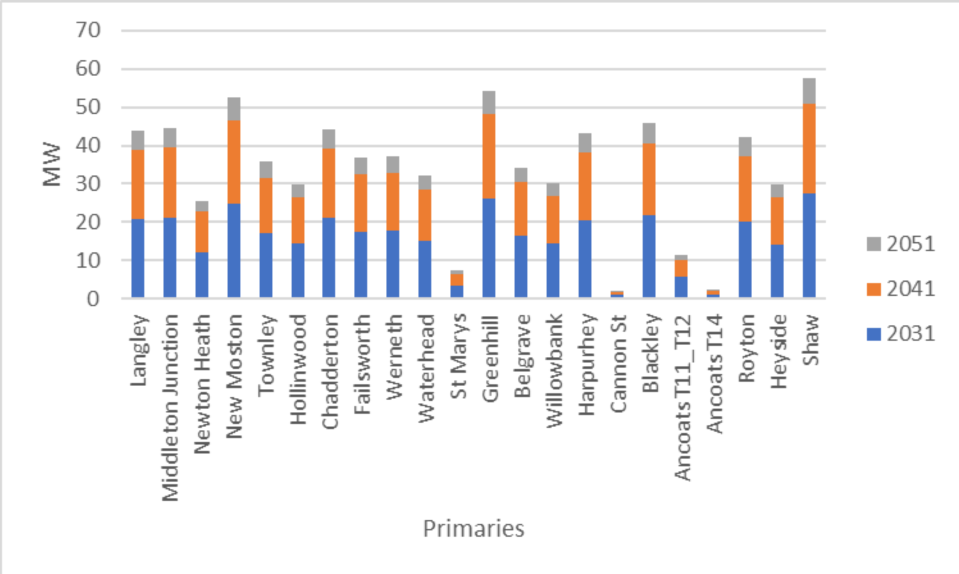

Figure 11: Primary Substation EV Demand Growth (Steady Progression)

For consumer transformation greater uptake of EV's are forecast, shown in Table 13, expressed graphically in Figure 12.

Table 13 - EV Update Using Consumer Transformation Forecast (MW)

BSP	Primary Substation	2031	2041	2051
Chadderton	Langley	31	29	5
Chadderton	Middleton Junction	31	30	5
Chadderton	Newton Heath	18	17	3
Chadderton	New Moston	37	35	6
Chadderton	Townley	25	24	4
Chadderton	Hollinwood	21	20	3
Chadderton	Chadderton	31	29	5
Chadderton	Failsworth	26	25	4
Greenhill	Werneth	26	24	4
Greenhill	Waterhead	23	21	4
Greenhill	St Marys	5	5	1
Greenhill	Greenhill	38	36	6
Greenhill	Belgrave	24	23	4
Greenhill	Willowbank	21	20	3
Redbank	Harpurhey	30	29	5
Redbank	Cannon St	1	1	0
Redbank	Blackley	32	30	5

BSP	Primary Substation	2031	2041	2051
Redbank	Ancoats T11_T12	8	7	1
Redbank	Ancoats T14	2	1	0
Royton	Royton	29	28	5
Royton	Heyside	21	20	3
Royton	Shaw	41	38	6

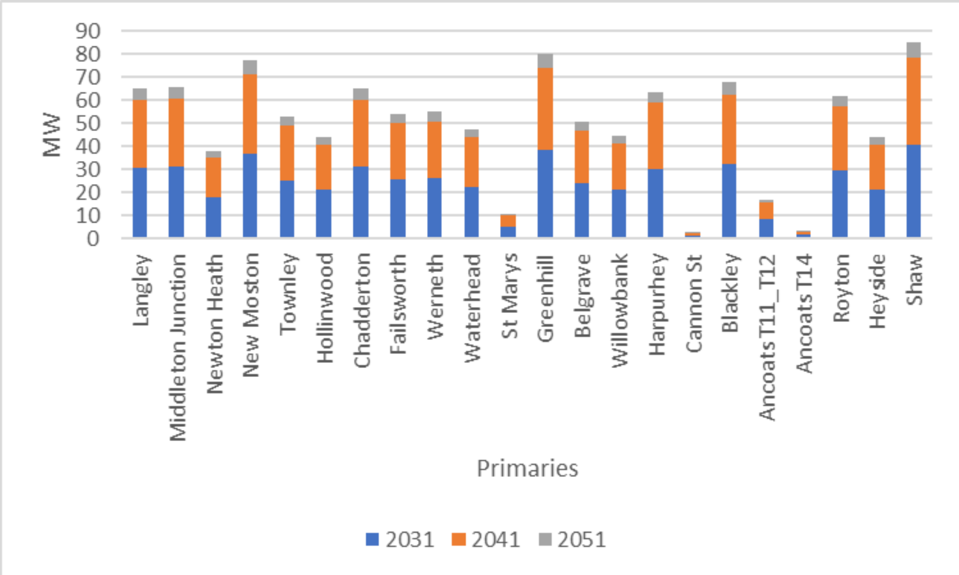

Figure 12: Primary Substation EV Demand Growth (Consumer Transformation)

Finally, heat pump uptake for steady progression is shown in Table 14 and represented graphically in Figure 13.

Table 14 - Heat Pump Uptake Using Steady Progression Forecast

BSP	Primary Substation	2031	2041	2051
Chadderton	Langley	9	12	8
Chadderton	Middleton Junction	6	8	6
Chadderton	Newton Heath	6	8	5
Chadderton	New Moston	9	15	11
Chadderton	Townley	3	4	2
Chadderton	Hollinwood	3	3	2
Chadderton	Chadderton	3	4	3
Chadderton	Failsworth	5	6	4
Greenhill	Werneth	4	4	3
Greenhill	Waterhead	4	5	3
Greenhill	St Marys	1	3	4
Greenhill	Greenhill	6	8	5
Greenhill	Belgrave	4	5	3
Greenhill	Willowbank	3	5	4
Redbank	Harpurhey	11	14	9
Redbank	Cannon St	1	1	0

BSP	Primary Substation	2031	2041	2051
Redbank	Blackley	8	11	8
Redbank	Ancoats T11_T12	4	4	3
Redbank	Ancoats T14	1	1	0
Royton	Royton	5	6	4
Royton	Heyside	3	4	3
Royton	Shaw	5	7	4

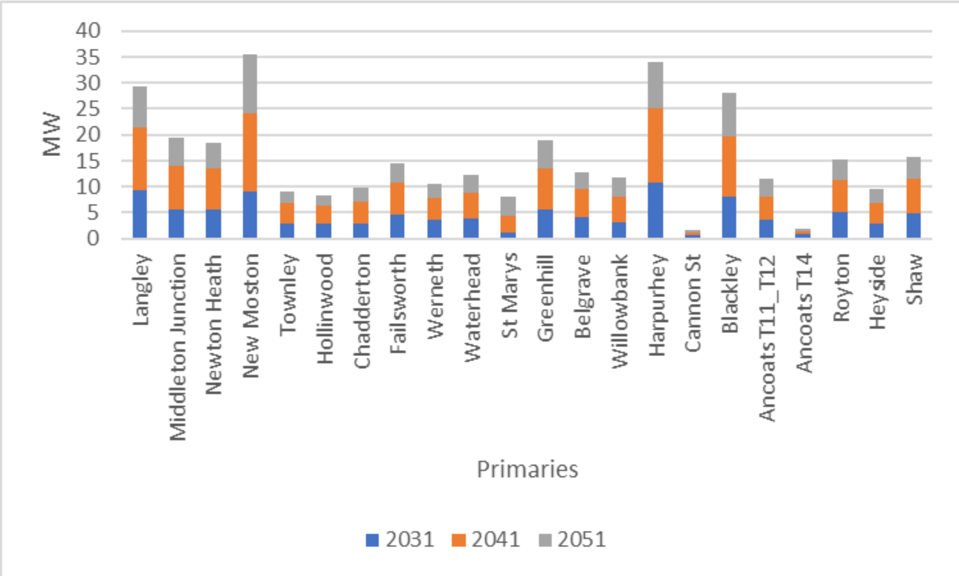

Figure 13: Primary Substation HP Demand Growth (Steady Progression)

The growth for consumer transform is shown in Table 15 and represented graphically in Figure 14.

Table 15 - Heat Pump Uptake Using Consumer Transformation Forecast

BSP	Primary Substation	2031	2041	2051
Chadderton	Langley	20	59	65
Chadderton	Middleton Junction	11	42	48
Chadderton	Newton Heath	11	34	38
Chadderton	New Moston	19	52	52
Chadderton	Townley	5	20	23
Chadderton	Hollinwood	7	24	28
Chadderton	Chadderton	6	28	33
Chadderton	Failsworth	9	40	48
Greenhill	Werneth	8	31	37
Greenhill	Waterhead	9	35	41
Greenhill	St Marys	5	13	12
Greenhill	Greenhill	12	55	65
Greenhill	Belgrave	10	36	42
Greenhill	Willowbank	8	32	36
Redbank	Harpurhey	20	57	62
Redbank	Cannon St	2	6	7

BSP	Primary Substation	2031	2041	2051
Redbank	Blackley	18	43	45
Redbank	Ancoats T11_T12	11	29	33
Redbank	Ancoats T14	4	8	9
Royton	Royton	11	45	54
Royton	Heyside	7	27	31
Royton	Shaw	9	45	55

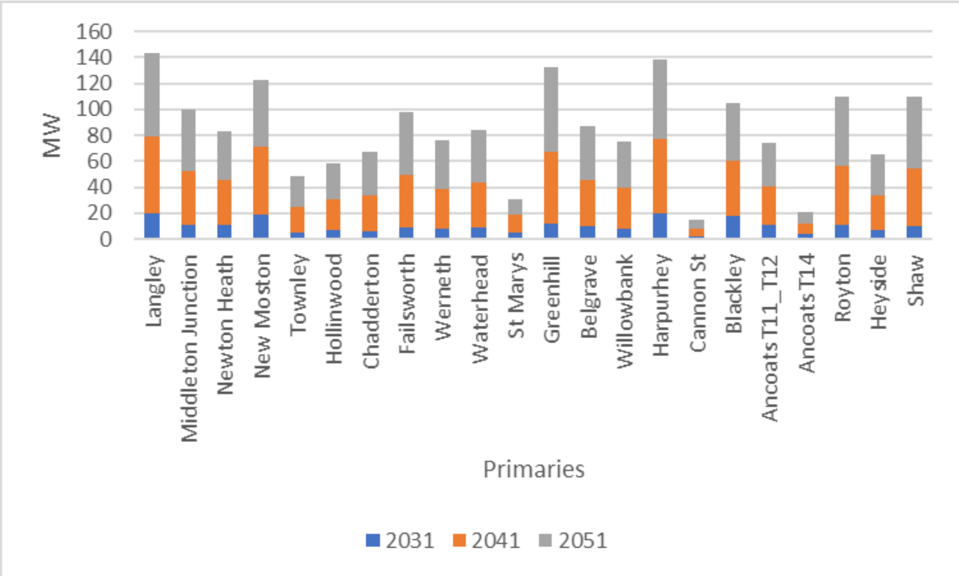

Figure 14: Primary Substation HP Demand Growth (Consumer Transformation)

Having the Load Growth Maximum is important to identify growth, but worst-case growth is not particularly useful in a flexible future. Therefore, a demand behaviour over time (time-series profile) is also needed to be associated with load growth to model the operational challenges correctly.

8.1.2. Load Magnitude Behaviour

The time-series behaviour of EV and Heat-Pump demand growth should also be decoupled from general DCI loads as their behaviour will be distinct and associated with large capacity of growth.

ENWL has used historical data in their DFES to determine the general demand profile for both types of load. The forecast typical charging profile for EV at present and at time points in the future are shown in Figure 15.

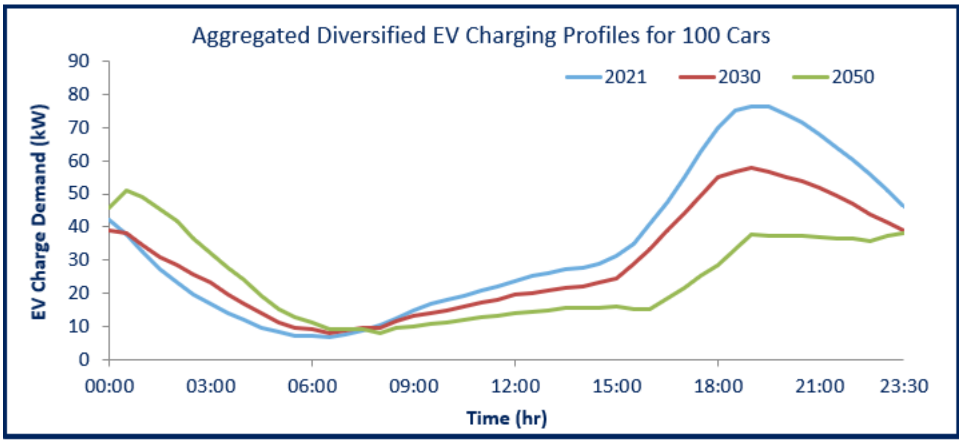

Figure 15 - EV Charging Profile for 100 Cars

The typical heat-pump demand profiles, present and future are shown in Figure 16.

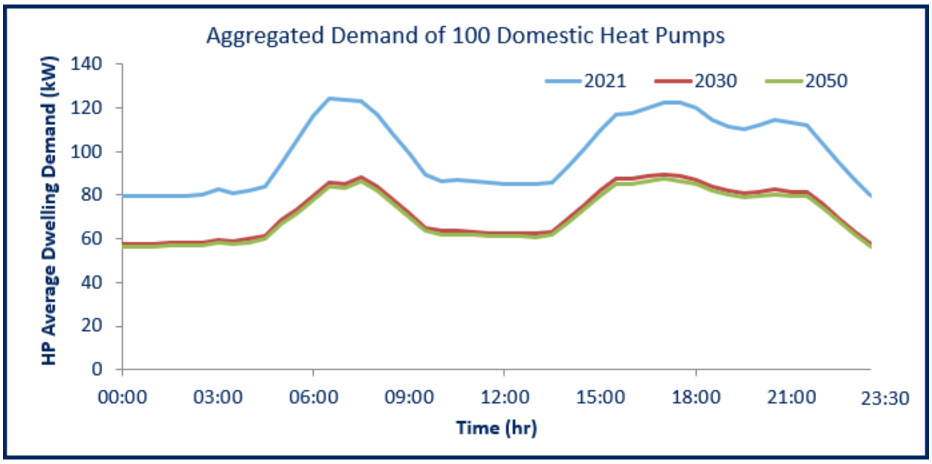

Figure 16 - Heat Pump Demand Profile for 100 Domestic Heat Pumps

The time series behaviour profiles can be coupled with magnitude to allow for operational scenario analysis.

<u>DCI Load Behaviour</u>

Existing loading trends from historical records can be associated with Domestic, Commercial and Industrial load behaviour, and associated with the primary substations where all these customers are mixed, as highlighted in Figure 17. Where large distinct customer connection behaviour can be set by the operation of the customer site these are not included within this load profile.

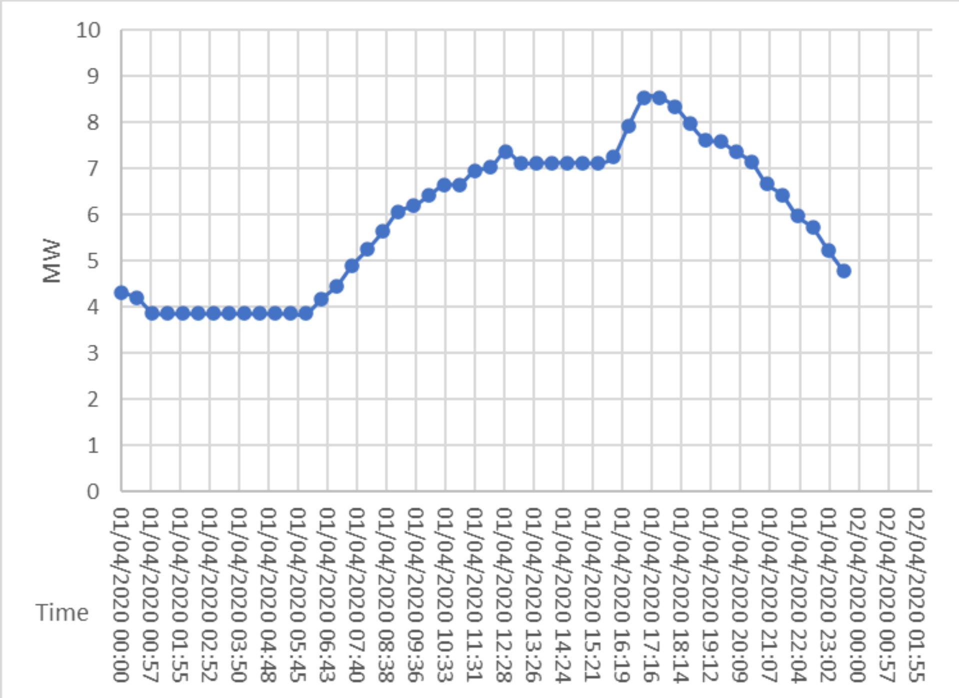

Figure 17: Typical Load Demand Profile for DCI load.

The aforementioned give us two out of the three major pieces of data we need to model load growth for operational challenges:

- Load Magnitude Growth: Data can be provided by the DFES scenarios
- Load Behaviour: Data can be provided by load behaviour embedded in the historical loading record.

Although magnitude growth will impact how the network will be loaded, and the time-series data expresses how the magnitude export will change across time, the exact impact of this growth at an instantaneous moment in time will be altered where a voltage-demand relationships exists.

The next section will determine how the magnitude growth, for each time-step, will also be affected by the underlying voltage demand relationship and how this itself will change during the next 30 years.

8.2. Load Type Behaviour Change

At the instantaneous moment of MW demand, voltage changes can affect the exact power required at that moment, governed by the type of load being satisfied.

As shown in the previous section this load will vary across a day and season, due to the underlying loads connected at that moment in time.

To understand how load type will change in the future SGS has investigated the main load types associated with the three main load growth areas.

- EV
- Heat Pumps
- DCI loads

The two major growth magnitudes on the network, EV and heat pumps are constant power loads and will not be affected by voltage change.

For EV this has been proven experimentally[5], this is shown in detail in Figure 18.

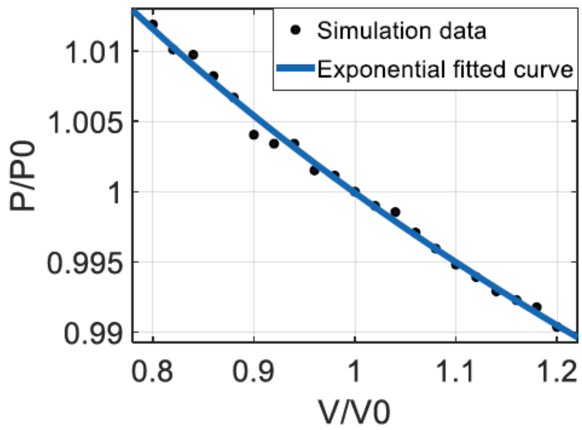

Figure 18: Extract from Electric Vehicle Charger Static and Dynamic Modelling for Power System Studies showing EV Charger Exponential Load Relationship

Where

$$K_p = log_{10}(\frac{P}{P_o})/log_{10}(\frac{v}{v_o})$$

$$K_p = log_{10}(1)/log_{10}(1)$$

$$K_p = 0$$

Therefore, any EV growth should be modelled as constant power.

For Heat-Pumps, due to Ecodesign legislation [6], all new heat pumps should be fitted with a variable speed drive, effectively making the load voltage independent. Only previously connected, older heat-pumps already integrated into the network will benefit from voltage variability.

That means, only modelling the domestic, industrial and commercial mixed, embedded demand needs to exhibit a non-constant power voltage demand relationship.

Domestic, commercial, industrial loads can be described as a mix of the following loads:

- Appliances:
    - Showers
    - Cold (refrigeration)
    - Wet (washing machines)
    - Audio-visual
    - ICT
    - Pumps
    - Other

[5] Energies: Electric Vehicle Charger Static and Dynamic Modelling for Power System Studies: *Hengqing Tian, Dimitrios Tzelepis and Panagiotis N. Papadopoulos*

[6] https://www.gov.uk/guidance/placing-energy-related-products-on-the-uk-market#what-is-covered

- Lights

The Standard Assessment Procedure for Energy Rating of Dwellings (SAP) put together a principle paper determining how these load types will change into the future. It has been summarised here, Table 16:

Table 16: SAP Paper Overview

Loads		Voltage-Demand Relationship Historical	Justification	Voltage-Demand Relationship Future	Justification
Appliances	Showers	Z	Most existing showers use resistive loading to heat water.	Z	No real alternative. However, does affect performance.
	Cold (Fridge Freezers)	Z	Most existing fridge freezers use grid frequency AC motors as compressors.	ZI	European Commission Regulation (EC) No 643/2009 is intended to improve the efficiency of refrigeration appliances. This is expected to result in new models increasingly using variable speed drive controls, decoupling their energy use from the supply voltage.
	Wet (Washing Machines)	Z	Most existing washing machines use grid frequency AC motors as drum drive.	ZI	Commission Regulations (EC) 1015/2010, 1016/2010, and others, are intended to improve the efficiency of domestic wet appliances. Therefore, move to variable speed drive.
	Audio-visual (Televisions, Radios)	ZI	Some older TVs which are Cathode-Ray Televisions contain transformers, exhibit resistive demand, whereas later LCD/LED TVs use solid state electronics with switch-mode power supply (PSU)	ZI	Depending on manufacturer design, some may keep small HF transformers, others may move to full switch-mode power supply.

Loads		Voltage-Demand Relationship Historical	Justification	Voltage-Demand Relationship Future	Justification
	ICT (Computers, charged devices)	IP	Almost all use voltage regulating power supply units.	P	Switch-Mode power Supply to fully improve and dominate.
	Pumps	ZI	Older pumps use grid AC frequency to drive pump.	P	Commission Regulation (EC) No 641/2009 will move new appliance to variable speed drive.
Light	Incandescent	Z	Older incandescent lights are resistive filament.	N/A	Prohibited in the UK
	LED	P	Need low variable voltage regulator to maintain field effect.	P	A full move to LED is expected.

The SAP paper table shows the development of most future loads are moving to a more voltage independent relationship, but not total. This analysis verifies what has been shown in the trends that the relationship between voltage and demand is weakening, and that this trend is likely to continue.

8.2.1.Trends Vs Discrete Load Prediction

The data provided by SAP could be used to provide a spread of load type across new DCI load connections, splitting the growth into independent constant impedance (Z), constant current (I) and constant power (P) portions depending on the number of customers, customer types (domestic, commercial, industrial), a full list of variables that would give you a mix of the resulting load type due to growth. However, this is limited and would suffer wildly from assumption variance.

As shown in the trend data, not all primaries are exhibiting these changes at the same speed, or at all.

Therefore, SGS recommends ENWL leverage their historical data trends to baseline their forecasts to predict the future shift in load type. Where the trend data per primary substation can be used to configure a forecast load type shift. This way the trends will be specific to the primary substation, based on what is happening and these changes can be monitored as time progresses to maintain accuracy of forecasts. By using trends, ENWL is less likely to under or overestimate both the benefits and limitations extracted from voltage-demand relationships as these forecasts are linked to progression of the present trends.

In the next section we examine how the ZIP model and trend data are utilised to provide a forecast of these changing voltage demand relationships. This is then coupled with load growth magnitude, and time-series behaviour to provide ENWL with a full representation of load for determining operational control impacts moving into the future.

8.3. ZIP model

Exponential load models (K_{EXP}) can be converted to ZIP models (K_Z, K_I, K_P) models, as described by M. Leinakse in [1]. The following sets of equations based on the value of K_{EXP}, used to determine which equation is required, are used to proportion the different aspects of the ZIP model:

$$K_{EXP} \leq 0 \rightarrow \begin{cases} K_Z = 0 \\ K_I = 0 \\ K_P = 1 \end{cases}$$

$$0 \leq K_{EXP} \leq 1 \rightarrow \begin{cases} K_Z = 0 \\ K_I = K_{EXP} \\ K_P = 1 - K_{EXP} \end{cases}$$

$$1 < K_{EXP} < 2 \rightarrow \begin{cases} K_Z = K_{EXP} - 1 \\ K_I = 2 - K_{EXP} \\ K_P = 0 \end{cases}$$

$$K_{EXP} \geq 2 \rightarrow \begin{cases} K_Z = 1 \\ K_I = 0 \\ K_P = 0 \end{cases}$$

By using the above set of equations and the predetermined K_{EXP}, it allows the make-up of a load to be identified as either constant impedance (Z), constant current (I), constant Power (P) or a combination of ZI or IP.

8.3.1.ZIP Model Conversion Results

The K_{EXP} obtained from the ENWL historical data for each primary substation within the BSP's (Chadderton, Greenhill, Redbank and Royton) were sorted for each year to provide load curves relating to K_{EXP}.

An example of such a load curve is illustrated in Figure 19, which shows the results for the Chadderton primary substation within the Chadderton BSP.

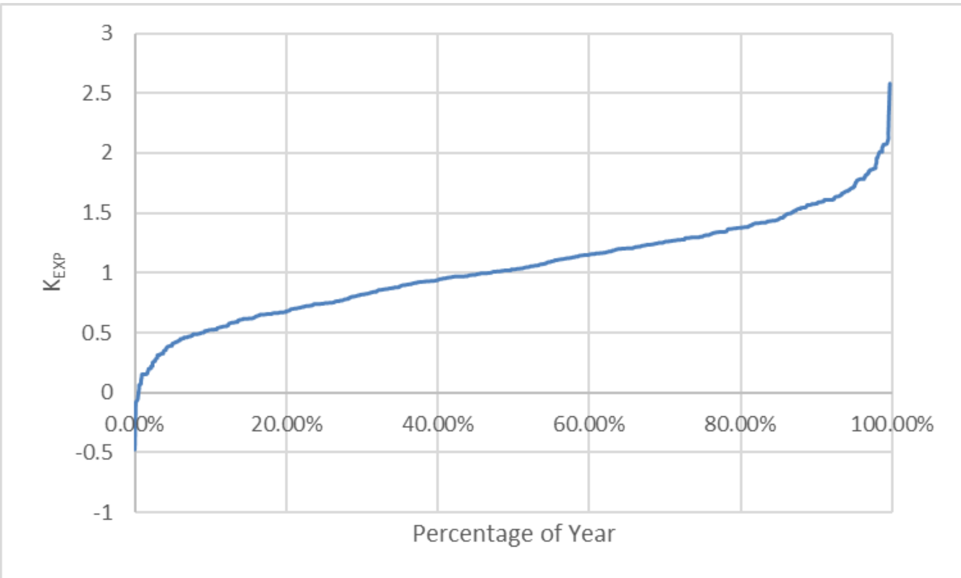

Figure 19: Load Curve expressed as K_{EXP} value over a year for Chadderton Primary

Following this, the equations outlined in the previous section, were used to calculate the ZIP model for each of the K_{EXP} data points obtained from the ENWL historical primary substation data. Again, this was conducted for each primary substation in each of the four BSPs outlined above, but only the ZIP results for Chadderton primary substation within the Chadderton BSP are illustrated below as a load curve in Figure 20 over a year. In these results:

- Ki is shown to be >0 and <1 for 100% of the year
- Where Kp and Kz are shown to be >0 and <1 for approximately 50% of the year.

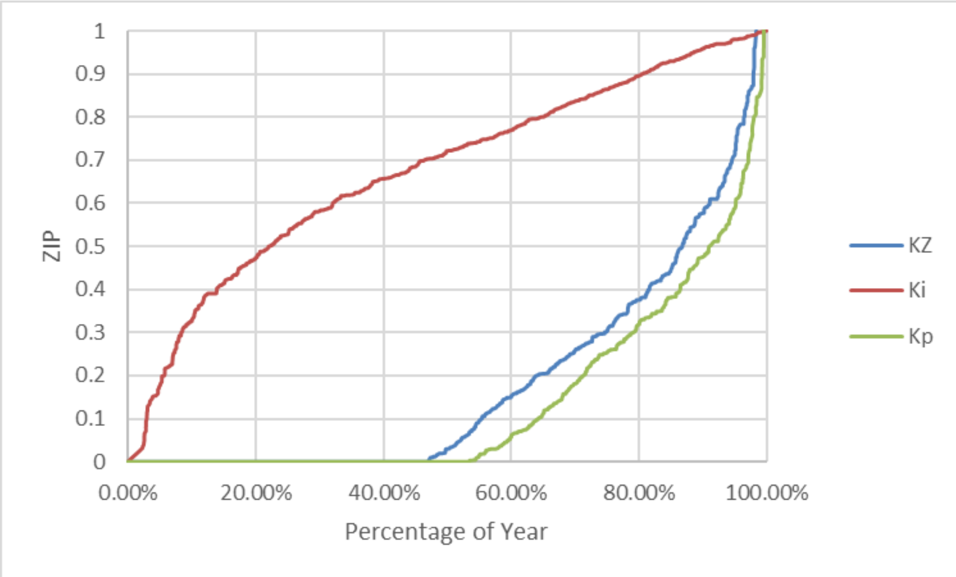

Figure 20: Load Curve expressed as K_Z, K_I and K_P value over a year for Chadderton Primary

8.4. Future Load ZIP Conversion

Historical K_{EXP} data, supplied from the ENWL historian, is used to provide a baseline of ZIP conversion for the year of data recordings. This follows the process as performed in Section 8.3.1. ZIP model conversion is limited, as it only represents loads as either a combination of ZI or IP, i.e. a load cannot consist of only constant impedance (Z) or constant power (P) components. This is further reiterated by the set of equations in the previous section, where K_Z and K_P always have a zero value if the other is non-zero.

However, in reality we know that loads can change from Z to P. Therefore, in order to capture this impact we suggest using the current ZIP model conversion for the present year (2022) load to allow the underlying load behaviour to be determined as a starting point in the analysis. This provides a baseline for developing ZIP models for future loads in the network.

We propose a novel approach to proportion the changes in the loads using the percentage changes of voltage-demand relationship trends to change the values, identified in the Exponential to ZIP conversion, from constant impedance (K_Z) to constant current (K_I) and a further change from constant current (K_i) to constant power (K_P) from each year to the next between each aspect of the ZIP model. This allows a value for Z, I and P in some instances across the load modelling providing an extension to the current ZIP load models. This provides a more reflective and realistic view of load type combinations in an electrical system, and the voltage relationship, and their changes, with each load type.

For example, an average increase of 5% between ZIP model proportions in the analysis was determined from the results in Table 9.

The approach outlined above enables the addition of future load development trends below a primary substation transformer to be captured within the future load models since loads can be either Z, I and P individually or a combination of these.

8.5. ZIP Model Changes

As mentioned in Section 8.4, after obtaining initial baseline values for each component of the ZIP model for the present load models a change of 5% of K_Z to K_I and a further 4% change of K_I to K_P was observed on the initial, 2022 ZIP model values. This percentage change was applied to the ZIP model for each year to obtain the next years proportions. Load curves were developed for each primary substation in each BSP as before, these are illustrated for Chadderton primary substation in the Chadderton BSP for K_Z (Figure 21), K_I (Figure 22) and K_P (Figure 23) for the present year (2022) and subsequent years of 2030, 2040 and 2050.

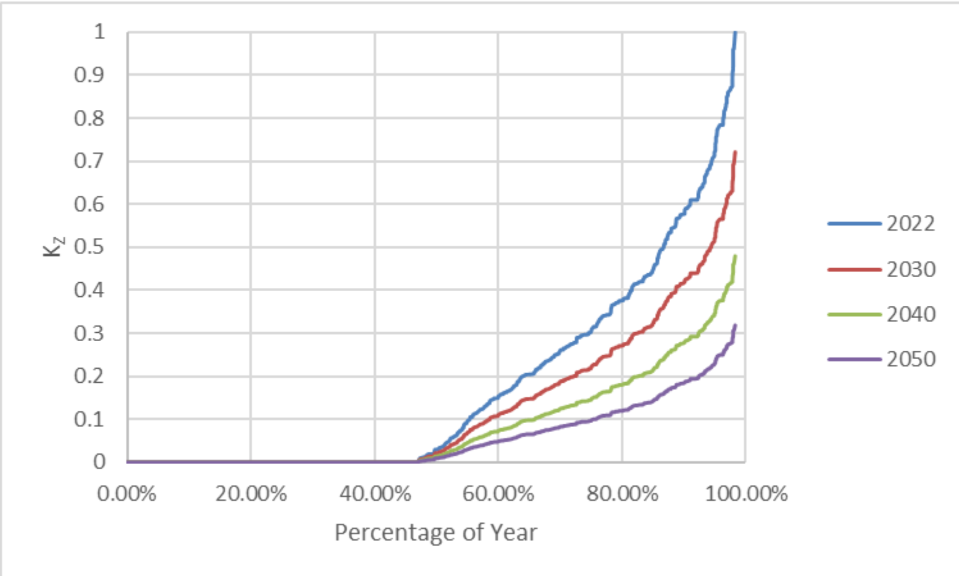

Figure 21: Load Curve expressed as K_Z, value over 2022, 2030, 2040 and 2050 for Chadderton Primary Substation

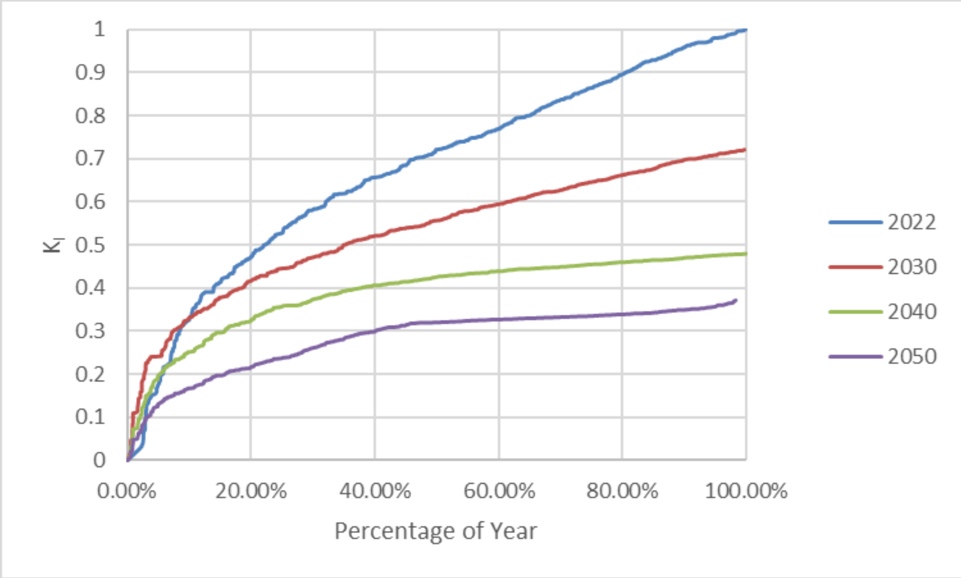

Figure 22: Load Curve expressed as K_I, value over 2022, 2030, 2040 and 2050 for Chadderton Primary Substation

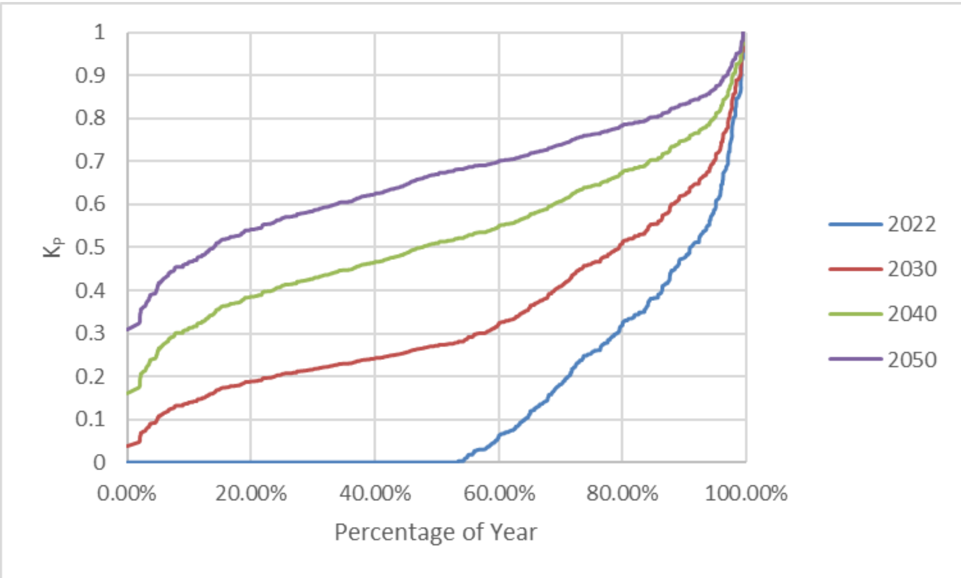

Figure 23: Load Curve expressed as K_P, value over 2022, 2030, 2040 and 2050 for Chadderton Primary Substation

An illustration of the yearly average for each ZIP component over the time of study (2022 – 2050) is provided below. This analysis has been conducted for all primary substation transformers fed from each BSP, but only one from each BSP is presented in this report.

Figure 24 illustrates the average yearly ZIP model proportions for the Chadderton primary transformer within the Chadderton BSP from 2022 to 2050.

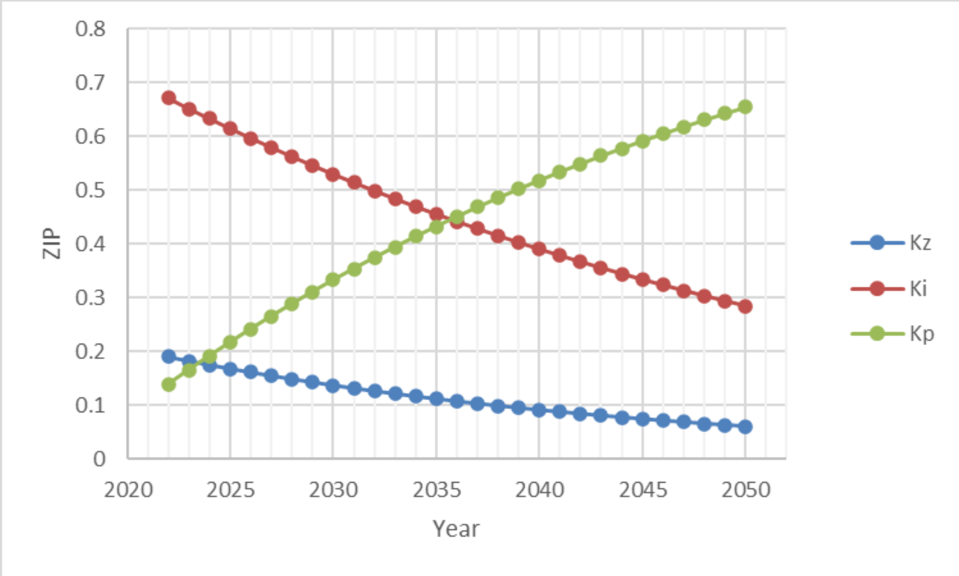

Figure 24: ZIP model changes at Chadderton primary transformer from 2022 to 2050

Figure 25 illustrates the average yearly ZIP model proportions for the St, Mary's primary transformer within the Greenhill BSP from 2022 to 2050.

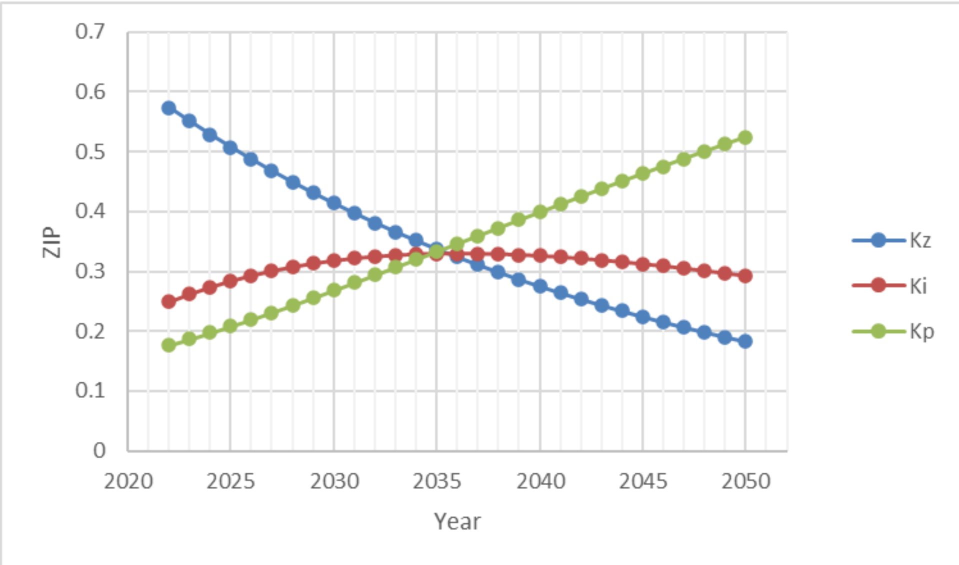

Figure 25: ZIP model changes at St. Mary's primary transformer from 2022 to 2050

Figure 26 illustrates the average yearly ZIP model proportions for the Blackley primary transformer within the Redbank BSP from 2022 to 2050.

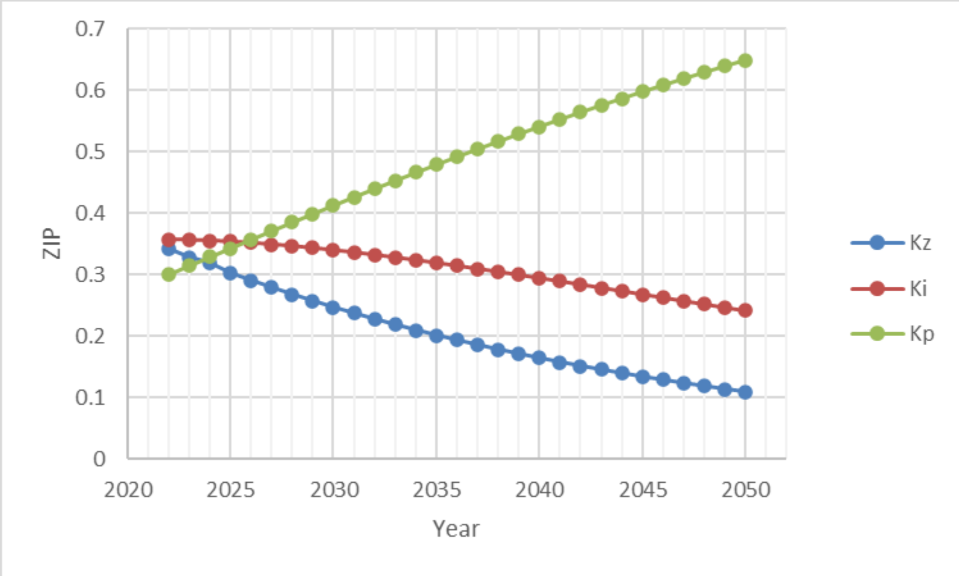

Figure 26: ZIP model changes at Blackley primary transformer from 2022 to 2050

Figure 27 illustrates the average yearly ZIP model proportions for the Royton primary transformer within the Royton BSP from 2022 to 2050.

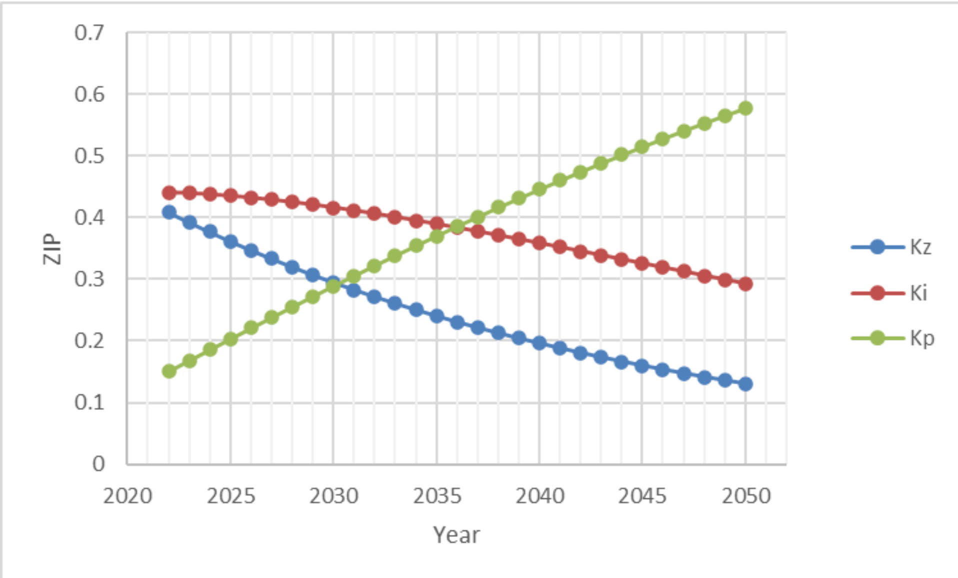

Figure 27: ZIP model changes at Royton primary transformer from 2022 to 2050

To summarise, it can be observed that for each of the primary transformers illustrated in Figure 24 - Figure 27 that K_Z reduces significantly from the levels determined in 2022 to 2050 before eventually starting to plateau. This aligns with load assumptions for future years in that certain resistive load technologies will not fully be replaced but the amount on the electricity system will reduce by less each year.

It can also be observed that the move to power electronic and current limiting devices is pushing more loads to K_I and K_P, with a substantial increase noticed in K_P over the studied timeframe.

The results and predicted trends of the ZIP model changes highlighted above were developed based on historical K_{EXP} datasets and future energy scenarios. It is recommended that the underlying trend assumptions are re-modelled periodically e.g. annually with any updates to improve the accuracy of these projections. Over a number of years this should start to improve the alignment of the future projections with reality.

8.6. Future Load Conclusions

For this part of the voltage demand relationship project we have developed a novel approach to allow us to proportion the changes in the loads between each part of the ZIP model across constant impedance (K_Z), constant current (K_I) and constant Power (K_P). This has extended the ZIP model to allow any combination of Z, I or P within a load model to be determined. This is required due to an underlying limitation of the existing ZIP modelling methodology, as it only allows representation of a load as either a combination of ZI or IP i.e. a load cannot consist of constant impedance (Z) and constant power (P) components.

The methodology was conducted by using a historical dataset of K_{EXP} model data, supplied by ENWL and measured from the primary transformer in each BSP, to provide a baseline value of ZIP conversion from K_{EXP} for 2022. This allowed the capture of underlying load make-up for each half hour over the initial study year, therefore allowing the proportion of the load which is constant impedance, constant current or constant power at each primary substation fed from each BSP to be calculated.

After obtaining the ZIP model from the present primary substation transformer K_{EXP} data, it was used in conjunction with the predicted ZIP model load trending data of a 5% change from K_Z to K_I and a change of 4% from K_I to K_P to provide a novel approach to proportion each part of the ZIP model for subsequent years in the study. This allows for values of Z, I and P, at certain instances over the study period, which could not occur using the traditional ZIP model methodology. This novel approach is reflective of realistic load type combinations and the voltage relationship with each type.

The approach outlined in Section 8.4 enables addition of future load development trends below a primary substation transformer to be captured within the future load models since loads can be either Z, I and P individually or in combination. The work undertaken in this section allows the study of the impact of the changing nature of load type within the electricity network. This is explored as part of the scenario analysis, which is developed in the next section.

9. SCENARIO ANALYSIS

The future load outputs are used as input data to create test scenarios for the final part of the report, presenting the impacts to the network of future load growth, and the effect voltage control will have on reducing these effects considering the changes to the future voltage demand relationship.

9.1. Input Data

In the previous sections three time-series data sets have been collected:

- MW Demand Growth Per Year,
- MW Demand per time-step,
- MW Demand relationship with Voltage per time-step: expressed either as an exponential model or ZIP model.

These data sets can create time step inputs to be applied to a power flow model. The first is the base power set point, as per the historic or forecast magnitude growth. The second is the kP values for an exponential model or kZ, kI, kP for a ZIP model.

9.2. Test Bench

Applying this data to the power flow model produces the operational steady state result of the ENWL network for each time step. When this is coupled with a control methodology, it closes the loop and results in a 'digital twin' presenting the as operated network and potential effects of control actions upon it. These actions can then be observed and provide situational awareness of the potential impact of controls across a time-series scenario window.

The test bench has been fully developed as part of the initial phase of the QUEST project[7], which implemented multiple control method and resolved issues between them. However, for this study, only the CLASS control method is used.

The test bench allows for CLASS Demand Reduction to be operated.

- CLASS Demand Reduction: Uses voltage control to decrease network real power demand by leveraging voltage-demand relationships. Its FUNCTIONS enable the following granularity of objective:
  - 100% - Demand Reduction Full: Function Level of 100% applies a voltage target of 0.95 p.u. nominal voltage at the secondary busbars at primary substations to achieve the CLASS demand MW target.
  - 75% - Demand Reduction Three Quarters: Function Level of 75% applies a voltage target of 0.9625 p.u. nominal voltage to achieve the CLASS demand MW target.
  - 50% - Demand Reduction Half: Function Level of 50% applies a voltage target of 0.975 p.u. nominal voltage to achieve the CLASS demand MW target.
  - 25% - Demand Reduction One Quarter: Function Level of 25% applies a voltage target of 0.9875 p.u. nominal voltage to achieve the CLASS demand MW target.

The test bench enables:

[7] 200952 15B ANM Research (WP5) - Functional Specification for Voltage Methodology and Scenario Analysis Issued

- Simulation representative of the ENWL electrical distribution system via network modelling for both time-step and time-series analysis, observing key performance indicators:
  - **Total System Demand:** Since this is a parameter that CLASS seeks to reduce it must be observed.
  - **33kV System Losses:** Since this is a parameter that CLASS will affect, it must be observed.
  - **External Network Generation[8]:** Since this is a parameter that will alter due to demand changes based on the applied time-series load profile, it must be observed.
  - **Internal Network Generation[9]:** Since this is a parameter that will alter due to demand changes based on the applied time-series load profile, it must be observed.
  - **Total System Carbon Intensity:** By converting external generation network MWh generation (ESO) and internal network MWh generation (DNO), to CO2 per kWh ENWL's carbon intensity can be determined. Showing how impacts to demand and generation can affect external and internal carbon intensity.

The input data, coupled with the developed test bench allows for the observation of key performance indicators important to ENWL to determine the service impact of CLASS for the future, that arise for changes to the underlying voltage-demand relationship. The scenario analysis will compare a potential network demand outcome in the future that can be compared to a scenario representative of today's operation. The difference observed across the key performance indicators will identify the potential changes in CLASS impact over the period analysed.

9.2.1. Baseline Scenario

This scenario sets the baseline operational scenario, capturing the highest demand month for the full Whitegate GSPs loading behaviour: (January 2022).

We set a constant Class MW demand reduction target of 20MW, above what we know the whole system is capable of. This is to show the maximum demand reduction the entire GSP can achieve, since, to meet the MW reduction, all CLASS sites will target a 100% reduction e.g., a 0.95 p.u. voltage target of nominal voltage.

Where each primary substation has its half-hour historical loading, assumed to be base power demand, applied for each time step across the month, to a load object.

An example graphical representation of the load make-up across the primary, distribution and LV substations is provided in Figure 28. Where the network has been modelled approximately to the end of an LV feeder, in order to monitor the voltage drop across every voltage level as a result of CLASS, or any voltage methods application.

At some primary substations, the modelling of the network has been expanded to include the primary feeders out to the distribution substations. Here the load recorded at the primary substation has been split to a 6/8 of it applied at the primary substation (representing 6 out of 8 approximate feeder connections), and the remaining 2/8 of demand applied to the two modelled distribution feeders.

At the distribution substation, the primary load measurement has been further split across the number of connected distribution substations. In the example provided in Figure 28 there are 10 distribution substations, therefore the load applied at each distribution substation is split into 10 equal parts.

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[8] generation required from outside the network under study (in this study this is attributed to the swing generator)

[9] generation with in the network (in this study all internal generation has been set to 0 MW)

At each distribution substation, load has been modelled as approximate LV feeders, further splitting the load with 4/6 of the demand applied to the LV demand (representing 4 out of 6 LV feeders), and the remaining 2/6 of demand modelled as approximate LV circuits. The approximated LV feeder demand has been split down each mid-way point. Finally, each midway point is split in half as depicted in Figure 28.

This details how the loads connecting to this extended model have been proportioned in line with the historic demand, as a fraction of the total primary substation historic load. In doing this, visibility of voltages at the end of the meter points are provided to increase confidence voltage reduction operations do not exceed statutory limits.

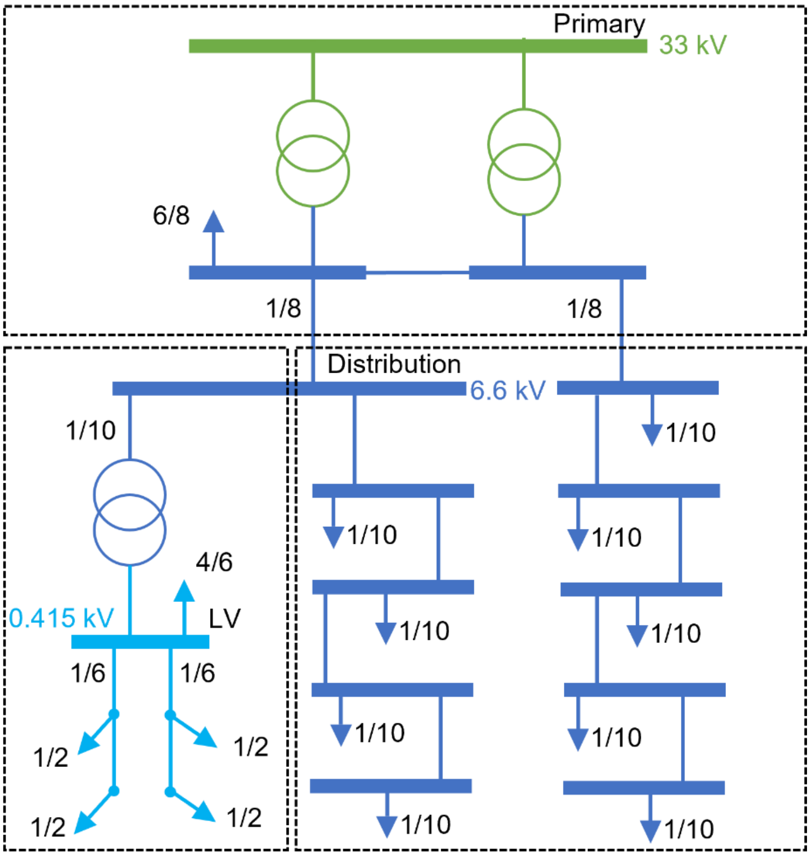

Figure 28: SLD of applied model load proportioning from primary load data received from ENWL

9.2.2. Baseline Scenario Results

The result for this scenario is shown in Table 17.

Table 17: 2022 Scenario Analysis

	Before TECHNIQUE applied	After TECHNIQUE applied	Difference	Before/After Percentage Change (%)
System Load (MW Average)	182.45	175.98	6.47	3.55%
System Generation External (MW Average)	183.74	177.21	6.53	3.55%
33kV Losses (MW Average)	0.8328	0.8009	0.03	0.00%
System Carbon (kgCO2 Average)	17323.69	16717.99	605.70	3.84%

9.2.3. 2031 Scenario

The 2031 Scenario takes the MW growth from Table 10, and the normalised time-series behaviour from the baseline scenario to re-scale the demand in line with this growth. The ZIP data for 2031 calculated from current trends, shown in Figure 20, are used to update the voltage-demand relationship. This input data is applied to the same test bench.

9.2.4. 2031 Scenario Results

The result for this scenario is shown in Table 18.

Table 18: 2031 Scenario analysis

	Before TECHNIQUE applied	After TECHNIQUE applied	Difference	Before/After Percentage Change (%)
System Load (MW Average)	237.33	231.15	6.17	2.60%
System Generation External (MW Average)	239.53	233.30	6.23	2.60%
33kV Losses (MW Average)	1.4136	1.3834	0.03	0.00%
System Carbon (kgCO2 Average)	22525.46	21950.52	574.93	2.13%

9.2.5. Scenario Analysis Conclusion

The scenario analysis has shown that, under present trends, for the month of January, the average MW demand reduction service for CLASS is 6.47MW by, 2031 this has degraded to 6.17MW, a reduction in service of approximately 5 % by 2031. Although it shows there is still a healthy amount of CLASS demand reduction service provision, this is a not insignificant drop based on current trends. This shows the importance of monitoring network demand trends, if this goes unmonitored and assumed to be flat ENWL could be offering service to the ESO of 95% of this.

Furthermore, the original network was used to investigate the 2031 scenario. At such high growth demand rates much of the network is outside equipment ratings. This made it difficult to model such growth as the model no longer converges under these high levels of demand across existing impedances (voltage collapse). Therefore, the model will have to include reinforcements, when they become necessary to consistently solve. This could be coupled with CLASS service provision to show how as a DSO service it could mitigate these required reinforcement works.

To improve the accuracy and precisions of the ZIP models, rather than using the average of the changes applied to all primary substations, each primary should be given its unique trend associated with its changing voltage demand relationship. This could be investigated as part of a wider exploratory analysis outside the scope of this work, where the focus has been on determining the methods of identifying and implementing the changing voltage-demand relationship, rather than establishing the most accurate and precise implementation and optimisation of these novel methodologies.

Finally, the scenario analysis provides ENWL with the tools to identify how the changes to voltage-demand relationship will affect the potential benefit of existing voltage control methods and future methods, such as Smart Street, as part of QUEST. This work has been fully integrated into the QUEST test bench and satisfies the issues raised by OFGEM that originally triggered the need for this work.

10. REFERENCES

[1] M. Leinakse and J. Kilter, "Exponential to ZIP and ZIP to exponential load model conversion: Methods and error," *IET Generation, Transmission & Distribution 15.2,* pp. 177-193, 2021.