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Investigating a Modelling Approach for a Variable VoLL

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GLOSSARY

Abbreviation	Term
CBA	Cost Benefit Analysis
CDSP	Central Data Service Provider
CI	Customer Interruptions
CNAIM	Common Network Asset Indices Methodology
CML	Customer Minutes Lost
DNO	Distribution Network Operator
DVLA	Driving and Vehicle Licensing Agency
EV	Electric Vehicle
ESO	Electricity System Operator
GB	Great Britain
GDP	Gross Domestic Product
GDPR	General Data Protection Regulation
IIS	Interruptions Incentive Scheme
I&C	Industrial and Commercial Customers
LCNI	Low Carbon Networks and Innovation Centre
LCT	Low Carbon Technology
LSOA	Lower Super Output Area
MSOA	Middle Super Output Area
NIA	Network Innovation Allowance

Ofgem	Office of Gas and Electricity Markets
ONS	Office for National Statistics
PSR	Priority Service Register
RIIO	Revenue = Incentives + Innovation + Outputs (Ofgem's performance-based framework to set the price controls)
RIIO-ED1	Electricity distribution price control 2015 to 2023
RIIO-ED2	Electricity distribution price control 2023 to 2028
RIIO-T1	Transmission price control 2013 to 2021
RMSE	Root Mean Squared Error
SAPE	Small Area Population Estimate
SHCS	Scottish Household Condition Survey
SIC	Standard Industry Classification
SME	Small and Medium Enterprise
SMS	Short Message Service
SPEN	Scottish Power Energy Networks
VoLL	Value of Lost Load
WTA	Willingness To Accept
WTP	Willingness To Pay

EXECUTIVE SUMMARY

Electricity North West tasked Frazer-Nash Consultancy with collating evidence show that the current single Value of Lost Load (VoLL) is outdated; and using this evidence, demonstrate that an improved estimate for VoLL could be developed.

The main task was producing a prototype model for variable VoLL that allows predictions of VoLL to be made for populations of customers using a small number of VoLL correlated characteristics. The insight gained in implementing this prototype model and subsequent assessment of its predictive accuracy allows conclusions to be drawn on the validity of deriving a variable VoLL model using the described approach.

What is VoLL?

VoLL is the economic metric of the value that customers put on the security of their electricity supply. There have been various methods used to calculate VoLL over the past decade; the most accurate estimation comes from the value that customers would be willing to accept in compensation if they were to experience an interruption. The current uniform VoLL established for RIIO-ED1 is £16,000/MWh, which was aligned to the Energy Not Supplied value used for RIIO-T1, set in 2011.

Desktop research conducted for Ofgem in 2012, ahead of the ED2 review, corroborated that this value was within the range established by the most recent international studies. Ofgem subsequently commissioned detailed customer research, conducted by London Economics in 2013, which included stated preference methods. The established VoLL estimation was based on a large-scale customer survey, which asked respondents their valuations and preferences in an assumed electricity outage scenario, and then mapped these to a corresponding estimation of VoLL (independent to the customer's income level). This study identified that VoLL was already starting to move ahead of the values underpinning ED1.

The Electricity North West Network Innovation Allowance (NIA)[1] project is the most recent and detailed study in this area. This was conducted in partnership with Impact Research and replicated the London Economics research to identify how VoLL has moved in the intervening period, using a consistent methodology.

This latest research identified that a significant further increase has occurred and that this is expected to continue with the acceleration in electrification of heat and transportation.

These findings suggest that the single 'average customer' VoLL estimate is out-dated and no longer accurate or appropriate. The variation in the financial and social impacts of supply interruptions across customer types is further highlighted within the Electricity North West research.

The influence of the decarbonisation agenda and increasing adoption of low carbon technologies (LCTs) is likely to increase the variation in VoLL across customer types and demographics. The growth in VoLL inaccuracy has significant implications for vulnerable electricity consumers, especially the fuel poor. These variations are not acknowledged within the single uniform VoLL used in RIIO-ED1 and may lead to inefficient investment decisions. The recent research suggests that there is a need for a more precise VoLL to reflect groups with significant VoLL variation, in order to more accurately support Distribution Network Operator (DNO) investment plans and policies.

Current Use of VoLL

The three key areas where VoLL is used within the regulatory mechanism of RIIO-ED1 are as follows:

- The parameter to set the marginal incentive rate for the frequency and duration of planned and unplanned supply interruptions within the Interruptions Incentive Scheme (IIS), i.e. the amount the DNO is rewarded or penalised if it improves or fails pre-defined targets;
- The network performance risk parameter within the Common Network Asset Indices Methodology

[1] ENWL VoLL Webpage: https://www.enwl.co.uk/voll

- (CNAIM), to derive the reference network performance cost of failure of assets; and
- The customer performance benefit in the scrutiny of investment decision calculations within the cost-benefit analysis model (CBA).

Ofgem use the single uniform £16,000/MWh VoLL as the starting point to calculate marginal incentive rates for each DNO, by applying relevant assumptions to output unique customer interruptions (CI) and customer minutes lost (CML) values. This process produces value of interruption and value of minute estimates, and these parameters can be used for other investment decision making processes and sensitivity analysis[2].

The IIS marginal rate rewards or penalises DNOs for performance against pre-set targets based on benchmarked and historical network performance data. The incentive balances the trade-off between the cost of improving reliability and the value customers place on this improvement. Ofgem do consider alternative incentive rates, if customer willingness to pay to avoid interruptions is greater than the single uniform VoLL provided, providing an example such as within the London area. According to recent research alternative incentive rates would need to be applied to each area, in order to eliminate any market inefficiencies within the mechanism.

When VoLL is used in the CBA model and CNAIM, DNOs are advised to use alternatives only when there is a significantly high demand customer. At present, and when justified, VoLL can be used in two ways—standard practice or enhancement—meaning that a DNO can tune the sensitivity of the customers served by a particular asset. This basic adjustment does not adequately differentiate between different customer types, which recent research suggests is leading to inefficiencies within investment decisions. A variable VoLL that reflects a more accurate representation of customer preferences, will allow the current investment mechanism to identify solutions that provide greater benefit to customers.

Deriving a Model for Variable VoLL

Customer survey data has been used to create a large number of artificial sample populations, each of which can be defined by values for a small number of VoLL indicators. This data set was used to train a prototype model that is able to predict the value of VoLL for any population for which the VoLL indicators are known. This VoLL model can therefore be used to extrapolate predictions of VoLL outside of the survey population, and has been used to make predictions of VoLL across the whole of Great Britain (GB) as part of this project.

The accuracy of this prototype model is assessed to be an improvement on the current approach—using a fixed uniform VoLL across the whole of GB. Further work is required to improve and characterise a version of the model that could be implemented into regulatory mechanisms. The findings outlined in this report suggest that the prototype model is able to estimate VoLL for a sample population with an accuracy approximately £2,000/MWh greater than a 'vanilla model' using the updated nationwide value of VoLL derived in the recent Electricity North West study.

However, it should also be noted that there is significant benefit to be gained from simply updating the single 'vanilla model' from the current Ofgem figure of £16,000/MWh[3] to the combined weighted average value of £25,300, established in the recent Electricity North West research.

The accuracy of VoLL assessments is also improved with simpler disaggregated models considering for example: just the variation in VoLL by domestic and small and medium enterprise (SME) customers, or just rural and urban customers. These conclusions should be considered carefully in determining the most appropriate next steps in the possible implementation of a variable VoLL model.

[2] Para 4.11 of Ofgem's document titled "Strategy decision for the RIIO-ED1 electricity distribution price control - Reliability and safety" quotes the link between the IIS, CI and CML setting for RIIO-ED1 to the VoLL set in RIIO-T1, of £16,000

[3] This has been inflated to 2012/13 prices

CONTENTS

1. INTRODUCTION

Electricity North West (ENWL) tasked Frazer-Nash Consultancy (Frazer-Nash) with developing a methodology for a functional variable value of lost load (VoLL). Currently, the electricity industry uses a single VoLL figure that is applied to all customers within RIIO-ED1[4], which is the price control that covers the eight-year period from 1 April 2015 to 31 March 2023. Previous Electricity North West research[5] has suggested that this figure is out-dated and the single value model is no longer appropriate, since it takes no account of outages on different types of customers or reflect consumers' future needs as part of a low carbon future transition.

The variable VoLL model developed by Frazer-Nash is constructed through a combination of functions and customer data. This allows VoLL figures to be established for a range of different customers, enabling more accurate information for different investment decisions.

This document is structured with a chapter summarising the key findings from the initial literature review to provide a background around the current use of VoLL in ED1 and the areas of inaccuracy that could be improved. The document then discusses the variable VoLL methodology model in detail. The modelling approach section describes the process used to derive a prototype model for variable VoLL and the accuracy and limitations of the prototype model. This is followed by recommendations for the implementation of a variable VoLL model and factors that should be considered for such a model in RIIO-ED2 and beyond. The report closes with conclusions and findings from the investigation surrounding the development of a variable VoLL methodology.

[4] RIIO (Revenue = Incentives + Innovation + Outputs) is Ofgem's performance-based framework to set the price controls.
[5] ENWL VoLL Webpage: https://www.enwl.co.uk/voll

2. UNDERSTANDING THE CONTEXT

2.1 WHAT IS VOLL?

The value of lost load (VoLL) is a concept developed in the early 1990s to represent the average value that electricity customers place on the security of their electricity supply. A recent study by Impact Research for Electricity North West builds on the existing VoLL research and describes VoLL value as a means "to evaluate 'disbenefit' to customers of a supply interruption of average duration" (Impact, 2019)[6]. In the research VoLL represents "the value that customers would be willing to accept in compensation if they experience an interruption" (Impact, 2019)[7].

Office of Gas and Electricity Markets' (Ofgem) strategy documents[8] acknowledge that there have been various methods to estimate VoLL, and each lead to different results. These include, but are not limited to:

- Macroeconomic methods (i.e. dividing gross domestic product (GDP) by energy consumed);
- Cost estimates based on previous loss of supply events / costs due to interruptions in the electricity supply.
- Customer surveys on willingness to pay (WTP);
- Customer surveys on willingness to accept (WTA);

These various methodologies produce a VoLL estimate for the financial and social cost of supply interruptions to customers, generally "in £ per MWh" (Electricity North West, 2017)[9]. Willingness to pay and willingness to accept methodologies were previously considered to have the best balance between practicality and accuracy. Nonetheless, recent work by Electricity North West reiterates the findings of the London Economics study[10]—that willingness to pay and willingness to accept methodologies result in significantly different VoLL estimates.

The Electricity North West 'Closedown report' explains that "customers' [willingness to accept] compensation for lost load is always much higher than the comparable [willingness to pay] figures for SMEs and domestic customers" (Electricity North West, 2019)[11].

The 'Closedown report' suggests—as does the London Economics study[12]—that the reason for this is "the psychological sense of loss from giving something up which feels greater than the gain from retaining it" (Electricity North West, 2019)[13]. This notion also demonstrates that "customers are generally far less willing to accept a decrease in supply reliability than pay for an improvement" (Electricity North West, 2019)[14]. The report shows that WTP is not an accurate reflection of the value consumers place on supply interruption, and suggests that "WTA is the

[6] Electricity Market Reform policy overview (p. 5)
[7] Electricity Market Reform policy overview (p. 5)
[8] The Ofgem strategy documents—relevant to this report—are the London Economics study (2013) The Value of Lost Load (VoLL) for Electricity in Great Britain, and the Desktop review and analysis of information on Value of Lost Load for RIIO-ED1 and associated work undertaken by RECKON (2012)
[9] Modelling Charging and Billing LCNI Conference (slide 3)
[10] The Value of Lost Load (VoLL) for Electricity in Great Britain
[11] VoLL Closedown Report - NIA ENWL010 (p. 13)
[12] The Value of Lost Load (VoLL) for Electricity in Great Britain,
[13] VoLL Closedown Report - NIA ENWL010 (p. 12)
[14] VoLL Closedown Report - NIA ENWL010 (p. 13)

most appropriate estimate to value security of supply for electricity" (Electricity North West, 2019)[15].

2.2 WHAT IS THE CURRENT VOLL?

The level of VoLL was established for RIIO-ED1 by Ofgem at £16,000/MWh, as the value that customers place on their security of supply. The VoLL for RIIO-ED1 was aligned to the Energy Not Supplied value used for RIIO-T1, set in 2011. The Electricity North West 'Closedown report' explains how this value "acts as a price signal for the adequate level of supply security in GB" and is a price indicator to identify where investment is required to deliver security of supply. (Electricity North West, 2019)[16].

Desktop research conducted for Ofgem in 2012[17] ahead of the ED1 review corroborated that this value was within the range revealed by recent international studies (on varying bases). Ofgem appointed London Economics to conducted further detailed customer research in 2013, which involved choice experiments within a study using stated preference methods. This study asked consumers their valuations and preferences in an electricity outage scenario, in order to establish the "prices to pay or receive to avoid or experience the outage" (LondonEconomics, 2013)[18]. The VoLL estimates were assigned to customers based on their answers to the survey, to remove influences from variations in income.

2.3 IS THIS VALUE STILL ACCURATE?

It is of note that the London Economic study in 2013 identified VoLL was already starting to move ahead of the values underpinning RIIO-ED1, with the research yielding a headline weighted-average VoLL figure of £16,940/MWh for peak winter workdays in GB (based on an average of the VoLLs across domestic and SME customers).

The most recent, detailed GB study in this area, was conducted under Electricity North West's Network Innovation Allowance (NIA) portfolio, in partnership with Impact Research. This project replicated the LE research to identify how VoLL has moved in the intervening period using a consistent methodology. The Electricity North West methodology was not an exact replication of the London Economics approach[19]. The methodology involved, "extensive qualitative and quantitative customer and stakeholder engagement", to gain insight into "how VoLL is assessed by different customer segments" (Electricity North West, 2019)[20].

The Impact research demonstrated that "VoLL is now notably higher than observed in the previous major GB study" (Impact, 2019)[21]. It has been hypothesised that this increase "reflect[s] a greater dependency on electricity and changing customer needs and expectations" (Impact, 2019)[22]. This upward trajectory is expected to continue with increasing uptake in the electrification of transport and heating.

[15] VoLL Closedown Report - NIA ENWL010 (p. 13)
[16] VoLL Closedown Report - NIA ENWL010 (p. 5)
[17] Desktop review and analysis of information on Value of Lost Load for RIIO-ED1 and associated work
[18] The Value of Lost Load (VoLL) for Electricity in Great Britain (p. 3)
[19] The differences are explained in Section 2.1 (p. 17) of the VoLL Key Findings (Phase-3) Report
[20] VoLL Closedown Report - NIA ENWL010 (p. 5)
[21] Electricity Market Reform policy overview (p. 5), the VoLL Key Findings (Phase-3) Report collaborates this, identifying that the repeated London Economics methodology calculation in 2018 was £25,301 MWh, compared to London Economics 2013 figure £16,940, when adjusted for inflation is only £18,500 (p. 13)
[22] Electricity Market Reform policy overview (p. 5)

This sentiment clearly identifies the need to develop a more accurate VoLL for RIIO-ED2[23], to reflect that VoLL can change considerably over time as consumer preferences evolve.

The Impact study concludes that, "a uniform VoLL significantly undervalues the needs of certain customer segments" (Impact, 2019)[24]. The determination of the original VoLL is based on the assumption "that all customers are impacted equally as a consequence of the loss of power and attach the same value to their supply reliability" (Impact, 2019)[25]. Current thinking suggests that this no longer reflects reality and that changing consumer preferences have significantly altered the value individuals place on having an uninterrupted electricity supply. The existing single VoLL model "fails to reflect the significant variation that exists in the financial and social impact of supply interruptions across different customer types" (Electricity North West, 2019)[26].

2.4 HOW COULD VOLL CHANGE?

The Impact study conveys the growing importance of identifying customer types, and the use of various, group specific VoLL estimates, to more accurately represent the total cost of interruptions. This is supported by numerous recent reports, which evidence the correlation between changing customer requirements and the need for a more accurate VoLL in a shifting electricity market.

The electricity market is currently facing significant changes driven by decarbonising energy in order to create a sustainable future. It has been documented within government literature and industry leading reports that electricity generation, transmission and distribution will all be affected. The National Grid suggests that the decisions we face for "achieving carbon reduction targets will ultimately, shape the energy system of the future" (ESO, 2019)[27]. This shift in the energy market will increase the value of VoLL estimates, diversity and size of variation. This implies that the need for increasing the accuracy of estimate values of VoLL will be even more important in the future than it is today.

Ofgem's 2011 'strategy for the [then] next transmission price control - RIIO-T1 outputs and incentives' report suggests that it was difficult to quantify VoLL since "VoLL is affected by several factors that impact on customers' energy use and hence the value they place on supply" (Ofgem, 2011)[28]. A list of group characteristics / factors that are believed to significantly vary values of VoLL follows[29]:

Customer group types and influences:

- Residential;
- Small/medium commercial and industrial enterprise (SME);
- Large commercial/industrial user;
- Business sector;
- Geographic location: rural or urban;

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[23] The next electricity distribution price control ("RIIO-ED2"), starts in April 2023.
[24] Electricity Market Reform policy overview (p. 5)
[25] Electricity Market Reform policy overview (p. 5)
[26] VoLL Closedown Report - NIA ENWL010 (p. 6)
[27] Future Energy Scenarios (p. 1) opening statement
[28] Strategy for the next transmission price control - RIIO-T1 Outputs and incentives (p. 43)
[29] It is worth noting that currently no comprehensive evidence exists for all influences, nevertheless, they are worth consideration if trying to achieve an accurate VoLL estimate for an individual with multiple customer type characteristics

- Geographic supplier: relevant regional DNO;
- Customer age;
- Number of children;
- Fuel poor;
- Vulnerable circumstance;
- MDE (medically dependent);
- Worst served;
- Socio-economic;
- Income;
- Affluence;
- Attitude;
- Domestic low carbon technology (LCT) users (solar, heat pumps etc.);
- Owner of electric vehicle (EV);
- Heating type (electric);
- Access to mains gas supply;
- Access to a support mechanism;
- Power cut experience;

Circumstance of Outage:

- Frequency;
- Duration;
- Scale;
- Season (summer or winter);
- Extreme weather conditions;
- Time of day (meal time or night time);
- Day of the week (weekdays or weekends – relationship changes for different customer types);
- Nature (planned or unplanned);
- Explanation to outage and supply restoration (via SMS, telephone, social media).

Vulnerability is highlighted within the Electricity North West's recent 'Closedown report', which states that "VoLL estimates are substantially higher for less affluent groups" particularly those considered fuel poor, even before adjustment to reflect income (Electricity North West, 2019)[30]. This suggests the current system neglects to reflect the requirements of those who are in most need of protection from loss of supply.

This demonstrates that Ofgem's focus "on identifying and tackling consumer vulnerability in the energy market is justified", recognising the importance that an individual's VoLL holds,

[30] VoLL Closedown Report - NIA ENWL010 (p. 6)

especially within vulnerable and dependent circumstances (Electricity North West, 2019)[31]. The justification for a more accurate reflection for these groups is apparent from the Electricity North West 'Closedown report', where a list of VoLL calculations for a number of customer types is provided, with the value of the highest domestic and SME estimates almost double that of the lowest.

The list of expected VoLL factors will be affected by electricity consumption trends for different consumer groups, driven by technology developments, and changes to consumer preferences, societal views, education and political stances. In particular, changes induced as part of a shift to a low carbon economy are highlighted, which will have "significant implications for DNO's long-term investment strategies" (Electricity North West, 2019)[32].

For instance, EV ownership is hypothesised to significantly increase an individual's VoLL, and notably, the 'Future Energy Scenarios' report predicts a large increase in EV use to help "decarbonise both transport and electricity supply for GB" (ESO, 2019)[33]. This suggests that an increasing reliance on electricity, driven by the decarbonisation agenda, will increase the need for more than one VoLL value.

EV ownership is not the only driving factor. The following list contains predictions that are expected to exist as part of a low carbon economy, which are likely to influence the range in values for the estimates of VoLL significantly. These factors should be considered to "ensure that future policy is driven by evolving customer needs" (Electricity North West, 2019)[34].

- Increasing number of EVs;
- Increase in electric heating in homes;
- Increase in quality of thermal insulation of house;
- Development of smart grids;
- Development in combined heat and power;
- Increase in "local" electricity generation;
- Unreliable electricity generation (dependent on non-controllable conditions)
- Increase in energy efficiency;
- Increase in storage viability.

It is worth noting that the pace and certainty of these changes is unknown. The Reckon report says that it would be unwise "to speculate how VOLL might develop over the next decade as a result of the emergence of features related to a change to a low carbon economy" (Reckon, 2012)[35]. Nonetheless, these considerations should be taken into account when determining VoLL by segment, to enable it to be fit for purpose for informing DNO policies and investment plans for ED2 over the next decade and beyond.

31 VoLL Closedown Report - NIA ENWL010 (p. 6)
32 VoLL Closedown Report - NIA ENWL010 (p. 10)
33 Future Energy Scenarios (p. 4)
34 VoLL Closedown Report - NIA ENWL010 (p. 23)
35 Desktop review and analysis of information on Value of Lost Load for RIIO-ED1 and associated work (p. 9)

2.5 HOW IS VOLL CURRENTLY USED FOR TRANSMISSION AND DISTRIBUTION PRICE CONTROL REGULATION?

Ofgem uses VoLL to inform decisions in price control determinations for both licensed DNOs and the Electricity System Operator (ESO) responsible for the GB electricity transmission network. In RIIO-ED1.

Ofgem aligned the IIS incentive rates with the “RIIO-T1 Energy Not Supplied” incentive (Ofgem, 2013)[36]. The incentive rate of the RIIO-T1 was designed by Ofgem “to reflect better the value customers place on electricity when they are without supply” (Ofgem, 2011)[37]. Ofgem’s estimate of VoLL was based on a review of literature from a number of sources, including: the views of industry stakeholders, macroeconomic studies and consumer survey estimates of VoLL from GB and other jurisdictions (NERA, 2015)[38].

A major application for a single, uniform VoLL is to create the “parameter to set the marginal rate, at which consumers’ value avoiding power cuts, within the RIIO Interruptions Incentive Scheme (IIS)” (Electricity North West, 2019)[39]. Through which, the parameter sets a baseline value for rewarding or penalising “DNOs for deviations in power cut performance against pre-set targets” (Electricity North West, 2019)[40]. Thus the IIS provides a financial efficiency incentive for DNOs to improve reliability and offers a mechanism to provoke DNOs to consider the interests of consumers and end users.

To obtain the IIS marginal incentive rate, for each DNO, Ofgem uses the uniform VoLL factor and translates it through an assumption based process, outputting a per minute factor customer interruptions (CI) and customer minutes lost (CML) values. These values reflect customer numbers for each regional operator and also include an ‘efficiency incentive’. Marginal rates are therefore unique to each DNO licence, despite being based on the same £16,000/MWh starting point. This calculation produces value of interruption and value of minute estimates for each DNO, which can be used for other investment decision making processes and sensitivity analysis.

DNOs that were deemed to have submitted better business plan forecasts received a higher efficiency incentive rate. This mechanism was introduced by Ofgem to “reduce the risk of companies gaming the price control settlement by inflating forecasts and then significantly underspending” (Ofgem, 2017) [41].

Since the IIS’ introduction in 2001, the “average [British] DNO [customer interruptions] and [customer minutes lost] performance has significantly improved”, demonstrating that a VoLL linked mechanism can have important consequences for consumers (Regulator, 2017)[42]. The utility regulator report highlights the economic principle behind this success, which revolves around the incentive rate being based on VoLL. This ensures optimum investment to improve reliability, by reflecting the “value that consumers place on secure supplies” (Ofgem, 2018)[43]. Therefore, the investment in reliability should reach “the point that marginal damage costs”-from

[36] Strategy decision for the RIIO-ED1 electricity distribution price control - Reliability and safety (p. 9)
[37] Strategy for the next transmission price control - RIIO-T1 Outputs and incentives (p. 44)
[38] Engineering Recommendation P2 Review Workstream 2.7, prepared for the Distribution Code Review Panel, P2 Working Group (pp. 7-8)
[39] VoLL Closedown Report - NIA ENWL010 (p. 34)
[40] VoLL Closedown Report - NIA ENWL010 (p. 34)
[41] Ofgem Guide to RIIO-ED1 2017 – (p. 55)
[42] Annex M Reliability Incentive (p. 9)
[43] RIIO-2 Sector Specific Methodology Annex: Electricity Transmission (p. 25)

loss of supply- are “equal to the marginal costs for ensuring interrupted electricity supply”, forming a stable market equilibrium (Regulator, 2017)[44].

Similarly, the RIIO-T1 Ofgem document explains that VoLL is used for the incentive, since it encourages economic efficiency in network investments through “the appropriate trade-off between cost of improving reliability and the value customers place on this improvement” — trade-off shown in Figure 1 (Ofgem, 2011)[45]. Ultimately, the IIS aims to drive DNOs to improve performance where it is most economically appropriate to do so; however, the regulation recognises that this can be disadvantageous to those served by poorly performing networks, where costly investment may deliver benefits to a relatively small number of customers. The worst-served allowance was included in the RIIO-ED1 to counterbalance the IIS. This is discussed further in Section 4.3.1.

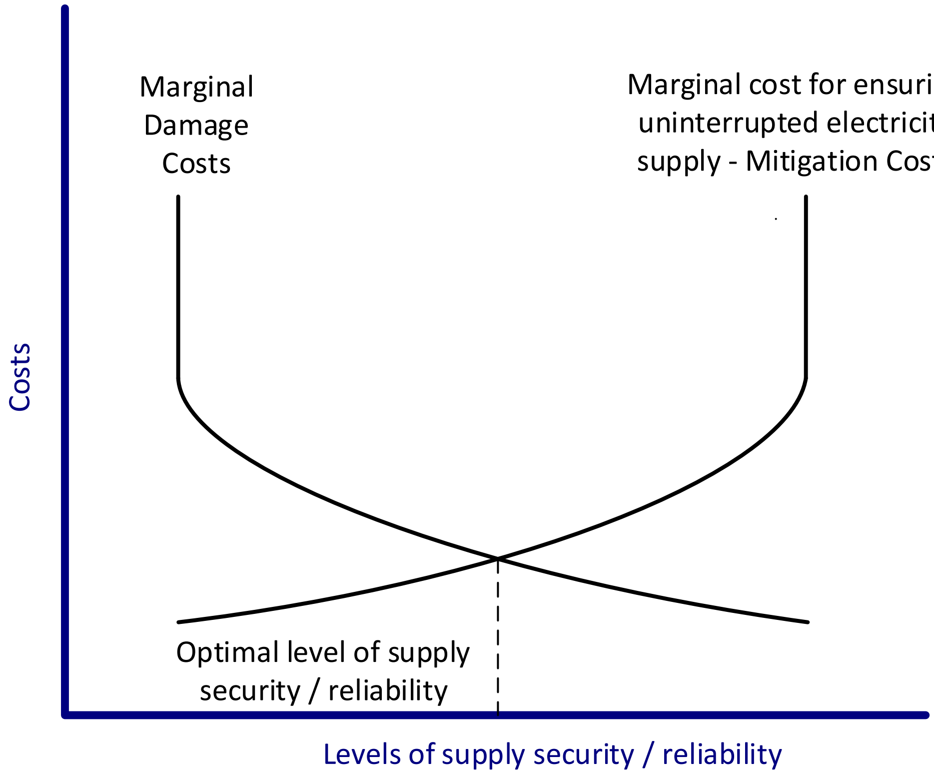

Figure 1[46]: Optimal level of supply security, showing the trade-off between cost of improving reliability and the value customers place on this improvement

Ofgem’s RIIO-ED1 documentation from 2013, advises that for consistency it is “appropriate to apply the efficiency incentive to the incentive rate under the IIS, across electricity transmission and distribution, as it reflects the same underlying impact on customers” (Ofgem, 2013)[47]. However, according to Ofgem’s recent literature this assumption for the same application across the two markets is considered to be ‘outdated’, for a uniform VoLL application. Whilst, the current uniform VoLL starting point within the IIS efficiency incentive rate methodology is also

[44] Annex M Reliability Incentive (p. 36)
[45] Strategy for the next transmission price control - RIIO-T1 Outputs and incentives (p. 43)
[46] Annex M Reliability Incentive (p. 36) - graph reconstructed by Frazer-Nash to improve image resolution.
[47] Strategy decision for the RIIO-ED1 electricity distribution price control - Reliability and safety (p. 31)

now under scrutiny by Ofgem, who recognise the need and "importance of using a precise value of VoLL that accurately reflects customer value" (Ofgem, 2018)[48].

Since the efficiency incentives are applied to the IIS incentive rates nationwide, Ofgem are "willing to consider DNOs setting their own incentive rates" within their business plan (Ofgem, 2013)[49]. This suggests that VoLL is only applied to reflect a specific customer group at the DNOs discretion. Ofgem's RIIO-ED1 reliability and safety report provides an example and suggests that DNOs might want to "put forward a case for alternative incentive rates" if "customer willingness to pay to avoid interruptions is greater (i.e. within the London area)" (Ofgem, 2013)[50]. Given that the literature reviewed suggests that customer WTP/WTA will vary for all regions and DNOs, not just individual customers, then DNOs should always put forward a well-justified alternative incentive rate within their business case.

The Scottish Power Energy Networks' (SPEN) 'Response to Ofgem's RIIO-2 Framework Consultation' challenges the current use of a uniform VoLL. The SPEN review suggests that for "each price control it is normal to review and, where appropriate, reset targets for incentive mechanisms and update other parameters" (SPEN, 2018)[51]. Then, the document suggests that in the future, incentive mechanisms should "take account of more recent research and estimates", demonstrating the understanding that the current use of VoLL within RIIO-ED1 for price control regulation contains inaccuracies and market inefficiencies (SPEN, 2018)[52].

Based on the collection of literature, and the recent SPEN review's suggestion, it would be reasonable to redefine the priority for updating the VoLL value or establishing appropriate levels of disaggregated VoLL for different customer groups, if price control regulation is to move towards market efficiency.

2.6 HOW IS VOLL CURRENTLY USED FOR INVESTMENT DECISION MAKING?

The VoLL estimate is important for DNOs when determining "network planning and investment strategies" (Electricity North West, 2019)[53]. In particular, VoLL is used as a defined calibration of the customer performance benefit during the scrutiny of investment decision calculations within the RIIO-ED1 cost benefit analysis (CBA) (Ofgem, 2014)[54].

Here, the single "fixed parameter" VoLL value is used to create relevant CI and CML factors, through the same calculation process as used previously in IIS rates, creating fixed static values linked back to the uniform VoLL (Ofgem, 2014)[55]. These factors are applied to calculate the benefits of an investment decision across the network and entire life of the asset/s, and to assess the financial consequences of proposed investment on network performance and customer impacts.

Notably, within Ofgem's RIIO-ED1 documentation that addressed stakeholder questions on the cost benefit analysis process, a query is made for Ofgem to "confirm that it is acceptable to use a VoLL option to measure benefit and test alternate location specific VoLL values" (Ofgem, 2014)[56]. Ofgem's response states that for consistency, they "encourage DNOs to use the same

[48] RIIO-2 Sector Specific Methodology Annex: Electricity Transmission (p. 30)
[49] Strategy decision for the RIIO-ED1 electricity distribution price control - Reliability and safety (p. 23)
[50] Strategy decision for the RIIO-ED1 electricity distribution price control - Reliability and safety (p. 31)
[51] SPEN Response to Ofgem's RIIO-2 Framework Consultation (p. 47)
[52] SPEN Response to Ofgem's RIIO-2 Framework Consultation (p. 47)
[53] VoLL Closedown Report - NIA ENWL010 (p. 5)
[54] RIIO-ED1 CBA guidance note 17 Jan 2014
[55] RIIO-ED1 CBA guidance note 17 Jan 2014
[56] RIIO-ED1 Cost Benefit Analysis (CBA), Supplementary guidance: queries and clarification 17 Jan 2014

approach to value interruptions/loss of supply i.e. the CI/CML fixed parameters included in the model" (Ofgem, 2014)[57].

The response implies that DNO's should apply a CI/CML methodology, for all options being considered throughout the CBA. Ofgem's response goes on to explain that "where a DNO has evidence, that it is appropriate to use a different assumption to those included in the model" (Ofgem, 2014)[58]. This suggests that DNOs can choose to apply the fixed parameter VoLL if there is an appropriate justification, specifically for customer types with a significantly increased VoLL variation.

Required justification is identical within the asset risk measurement approach of DNOs as set out in the Common Network Asset Indices Methodology (CNAIM). This is a common approach for the assessment, forecasting and regulatory reporting of asset health and criticality, which provides an indication of the risk of condition-based failure of network assets. This mechanism includes a reference network performance cost of failure for each asset type. This assesses the value on an interruption, which affects customers, if an asset fails. The risk measurement in CNAIM is intrinsically and inversely related to the benefits received from investment decision making in the Ofgem CBA model, with the CBA model quantifying the effect of mitigating the risk in the CNAIM.

In CNAIM, the single, uniform VoLL value is utilised to develop CI and CML factors, using the same calculation methodology, to create monetised network performance risk parameters used to identify the probability of failure and subsequent consequence. The CNAIM risk measurement approach provides a consistent way across networks to evaluate the condition based risk of assets, which means that any asset failure is assessed in the same way to allow for easy comparison.

Similarly to Ofgem's advice for CBA calculations, the DNO CNAIM report states that "DNOs can elect whether or not to apply this adjustment within their implementation methodology" (DNOs&NIE, 2017)[59]. The document suggests that VoLL is to be included as an adjustment factor for the CNAIM calculation of a network performance cost of failure only for "high demand customers" (DNOs&NIE, 2017)[60].

At present, VoLL, when justified can be used in two ways—standard practice or enhancement—allowing a DNO to tune the sensitivity of the customers served by a particular asset. However, the current use of this sensitivity tool is fairly sporadic and not consistently applied. The recent literature suggests that using the adjustment factor only for high demand customers produces inefficiencies within the risk measurement approach. Since, VoLL estimates vary significantly for most customer types, the use of VoLL should be compulsory for all significantly varied customers, high and low, in order to gain improved accuracy for investment case approval.

It is of note that inclusion of a customer sensitivity factor within the CNAIM by extension implies an existing need for a variable VoLL. However, it does not provide guidance on which scenarios are relevant, or indeed the justification or evidence required. This lack of clarity indicates that VoLL, specifically in relation to the sensitivity factor, is currently not applied by DNOs in a consistent manner, which reflects the diversity in customer types.

This perception is consistent within recent literature, and the idea that an adjustment factor only needs to be applied when an asset has "an exceptionally high demand per customer" is

57 RIIO-ED1 Cost Benefit Analysis (CBA), Supplementary guidance: queries and clarification 17 Jan 2014
58 RIIO-ED1 Cost Benefit Analysis (CBA), Supplementary guidance: queries and clarification 17 Jan 2014
59 DNO Common Network Asset Indices Methodology (p. 85)
60 DNO Common Network Asset Indices Methodology (pp. 85-86)

highlighted as the root of inaccuracy (DNOs&NIE, 2017)[61]. Enhanced methodologies, which account for the customer type and different estimates of VoLL would reduce the current inefficiencies in calculations and more accurately reflect the consequence of failure based on the need and reliance of customers served by an asset.

A similar conclusion can be reached for investment decision appraisal. For instance, the Electricity North West 'Closedown report' suggests that "understanding relative VoLL components at a much more granular level, will provide an opportunity for improvements in DNOs' current cost-benefit analysis models, which would deliver greater efficiency in future investment decisions" (Electricity North West, 2019)[62]. Therefore, building a deeper understanding of VoLL variation will enable a more accurate representation of customer preferences, and allow the current investment mechanism to provide solutions that reap more benefit to the customers.

61 DNO Common Network Asset Indices Methodology (p. 176)
62 VoLL Closedown Report - NIA ENWL010 (p. 26)

3. MODELLING APPROACH

3.1 OVERVIEW

Choice experiment data collected by Impact Research through a customer survey in 2016/17 has allowed detailed analysis to be undertaken on the extent to which VoLL varies amongst different types of customers. Information collected in the survey permits analysis to be undertaken in which customers are segmented by key demographic, socio-economic, geographic and behavioural factors.

Previous work by Impact Research has investigated the relative values of VoLL when making comparisons across single characteristics. This approach allowed the VoLL to be determined for rural as opposed to urban customers, or for male as compared to female customers etc. It demonstrated that VoLL did indeed vary substantially across different types of customers, and that these variations could be attributed to certain customer characteristics.

However, the approach was limited in that it remained unclear how to calculate VoLL estimates for real customers, each of whom can be defined by multiple characteristics. Each customer has a gender, an age and various defining socio-economic metrics and behaviours. Their property will also have geospatial characteristic ranging from a low density rural to a densely populated urban location. The Impact Research did not examine how to combine the estimates of VoLL for each of these individual characteristics to form an overall VoLL for the customer. This is the challenge in defining a model for a variable VoLL, and the starting point for this piece of work.

The model that has been developed as part of this piece of work allows users to estimate the VoLL for any given population, if the defining characteristics, or VoLL indicators, for the population are known. These indicators include the proportion of customers in fuel poverty, the electricity consumption of customers and the population rurality.

It is important to understand that the model does not allow you to estimate the VoLL for an individual, but rather the VoLL for a population of customers containing at least two hundred individuals. This limitation is a consequence of the Hierarchical Bayes analysis used by Impact Research to calculate values for willingness to accept. However, it is not believed to be a significant limitation to the approach, as most practical implications of such a model would involve estimating the VoLL for populations of customers and not individuals. Users would be able to estimate the VoLL in a range of different scenarios, from the customers living in a particular postcode area to the households/businesses served by a particular asset – be it a low voltage feeder or a primary substation.

The model delivered alongside this report is a prototype, designed to prove the concept and demonstrate to stakeholders the potential for such a model. It is just as important to understand the limitations as well as the advantages of the proposed approach, and both are set out in this report.

The current model uses a subset of the possible VoLL indicators, limited in part by the availability of GB-wide data to facilitate the predictions of VoLL across the whole of GB. It would be relatively straightforward to expand the model to account for additional data sets should they be made available. Additionally, the current model has been used to calculate the VoLL at a Lower Super Output Area (LSOA) level for all of GB. However, this has only been performed to demonstrate the granularity at which VoLL can be calculated using the model. It could also be used to make VoLL estimates for alternative geographic boundaries, such as those defined by DNO distribution system databases. These options are also explored in this report.

3.2 APPROACH

3.2.1 VoLL Calculation from the Customer Survey Data

In order to derive the model for a variable VoLL, it was necessary to be able to perform analysis of the customer survey data such that the VoLL could be calculated for subsets of survey respondents. The equation used to calculate VoLL is:

$$VoLL\ (£/MWh) = \frac{WTA\ (£)\ \times Income\ Factor}{Average\ Usage\ (MWh)\ \times Usage\ Factor}$$

Where WTA is the willingness to accept ‘an unplanned supply interruption lasting one hour and occurring at a time that would be most inconvenient’ for the customer. The income factor adjusts VoLL for the income of the customer segment, and has only been applied to fuel poor, vulnerable and low income customers. This is common practice in much economic analysis, justified on the basis that the value of an additional pound of income may be higher for a low-income recipient than a high income recipient. The denominator of the equation is the electricity consumption of the customers for which VoLL is being calculated. It is computed as an average usage adjusted by a factor to account for the usage of the customers being assessed.

The WTA itself is derived from the choice experiment data collected from the customers that completed the Impact Research survey. This survey was completed by approximately 6,500 customers, of which 5,000 were domestic customers and 1,500 were SMEs. The geographical distribution of the survey respondents is shown in Figure 2.

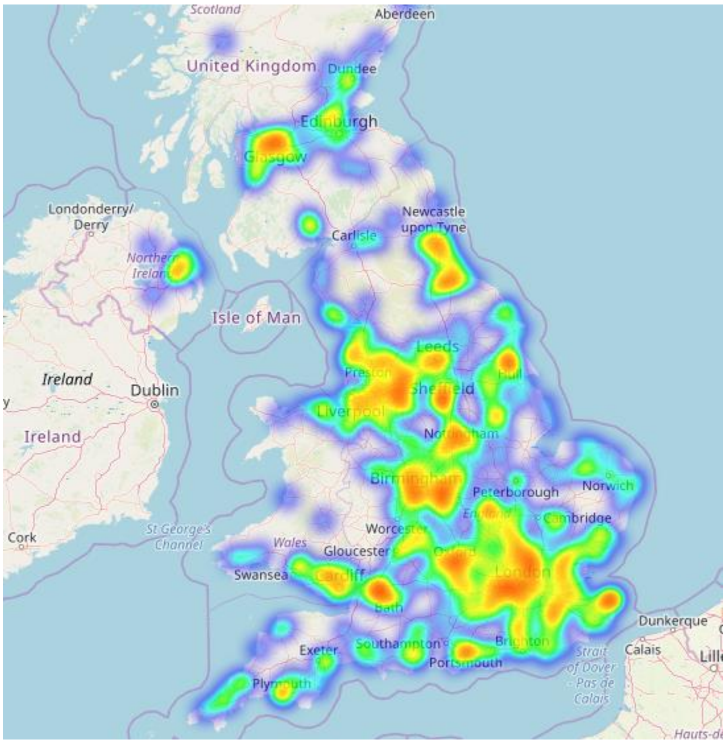

Figure 2: The locations of the approximately 6,500 survey respondents. More surveys responses were received from areas shaded in yellow and orange than those in blue or green.

Hierarchical Bayesian techniques can be used to analyse the discrete responses to the various trade-off scenarios in the survey and thus calculate an estimate for WTA for all respondents. By filtering the data for a subset of customers it is also possible to calculate a WTA, and therefore a VoLL, for smaller populations within the survey data – so long as they contain more than 200 respondents.

3.2.2 Creation of a Training Data Set from the Customer Survey Data

Rather than filtering the survey data for a single characteristic, the model has been derived from a large number of non-homogeneous populations containing respondents that display multiple characteristics. Each sample population can be defined by the following VoLL indicators:

- Rurality: urban / rural; each sample population is made up of entirely urban or rural customers.
- Age: the percentage of the sample population that falls into the 18-29, 30-44, 45-59 and 60+ age brackets.
- Income: the average income of the sample population.
- Consumption: the average electricity consumption of the sample population.
- Fuel poverty: the percentage of the sample population that is in fuel poverty.
- DE proportion[63]: the percentage of the sample population that fall into the DE socio-economic group (which includes the unemployed, unskilled manual workers and pensioners).
- Off-gas: the percentage of the sample population that is off the mains gas network.
- EV ownership: the percentage of the sample population that own EVs.
- Vulnerability: the percentage of the sample population classified as vulnerable.
- Experience of power cuts: the percentage of the sample population that have experienced a planned or unplanned power cut.

To create the training data set 100,000 sample populations of 250 respondents each were drawn from the customer survey. The urban and rural data was separated, and so 50,000 sample populations were created for each. The VoLL was calculated for each sample population and stored against the population's VoLL indicators. The diagram in Figure 3 describes the process for creating such sample populations from the survey data.

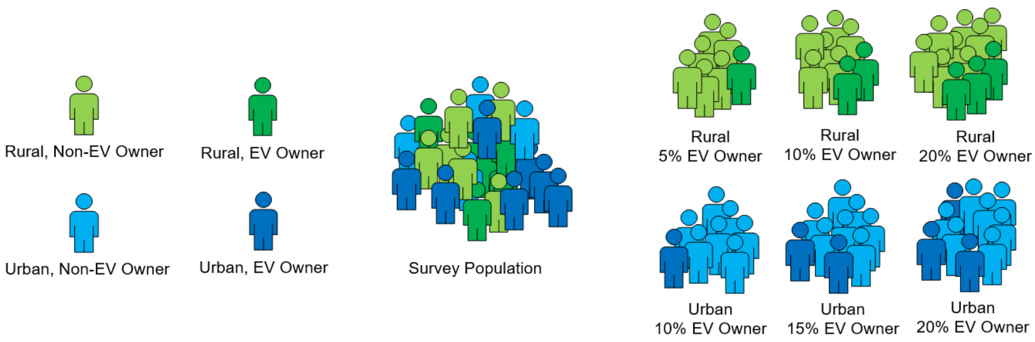

Figure 3: The process for creating sample populations from the survey data. In this instance only two VoLL indicators are shown (rurality and EV ownership), but the

[63] Social Grade: https://www.ukgeographics.co.uk/blog/social-grade-a-b-c1-c2-d-e

example illustrates how sample populations can be drawn from the survey data, and how these sample populations can be defined by their VoLL indicators. The VoLL for each sample population can then be recorded against the population's VoLL indicators.

Stratified sampling methods were used to ensure that a full range of values were present for each of the VoLL indicators in the training data set[64]. The analysis of the training data produced found a good match against the general distributions for GB for nearly all of the VoLL indicators. The only exception was the distribution of EV ownership, which was slightly higher in the survey data than the current penetration of EVs across GB in general. This was the result of the Electricity North West study specifically targeting a defined quota of LCT users to establish how future VoLL may vary in a low carbon future. Approximately 5% of the survey respondents were EV owners, compared with less than 1% of the population in general. This could mean that a model trained using this data would tend to slightly over-estimate VoLL, as EV owners tend to have a higher VoLL. However, the difference is just a small number of percentage points, and ownership is currently such a small percentage overall that it is not thought this will result in significant inaccuracy.

Training data was created using domestic customer survey data only, as it was only used to create a model for domestic VoLL. The approach for combining the domestic VoLL with SME VoLL is covered in Section 3.2.4.

3.2.3 Training the Domestic VoLL Model

The domestic VoLL model was trained using the 100,000 data points in the training data set, where each sample population and the corresponding VoLL value may be considered as a data point. The model is split into an urban and rural VoLL model, with each trained separately using the 50,000 data points created using the urban or rural customers respectively only.

Producing each model is classified as a regression problem as we are looking to predict a continuous value, i.e. the VoLL for the population. Since it is a regression problem it can be solved using supervised machine learning because we have labelled data for training the model (i.e. we know the value of VoLL for the data points in the training data set).

Several different types of machine learning models were trialled when producing the VoLL model. These included linear models, polynomial models, decision trees, random forests and support vector machines. It was found that a linear model performed best when assessed for accuracy against a withheld test data set. The fact that the training data is highly variable means that the more complex models tended to over fit to the training data[65]. Over fitting is a problem in which a model is able to make accurate predictions for the data it is trained with, but does not generalise well to new data.

Using a linear model to predict VoLL also carries the distinct advantage that it is simpler to interpret and explain. It means that when making a change to a particular VoLL indicator, the predicted VoLL always moves in the same direction. This is as opposed to some of the more complex machine learning models which may produce unintuitive results that are difficult to explain.

[64] It is important to note that the centre of the distribution of each VoLL indicator will always tend towards the centre of the distribution of the survey data set when creating a training data set in this way, which is not necessarily representative of the distributions of VoLL indicators across GB
[65] The training data being highly variable is a consequence of a fact that the survey is making an assessment of human preferences (a willingness to accept). The only way to increase the stability of the training data would be to collect more of it.

In deriving the VoLL model it was determined that some of the VoLL indicators were more significant than others. It was even observed that the inclusion of some VoLL indicators had the effect of reducing the accuracy of the overall model. This is attributed to the fact that there is high variability in the VoLL reported by customers and so an indicator must be significantly correlated in order to improve the accuracy of the model. Small correlations with VoLL are rapidly outweighed by the inaccuracies in predicting a value based on human preferences. As such the only VoLL indicators included in the final VoLL model were[66]:

- Rurality;
- Income;
- Electricity consumption;
- Socio-economic status (i.e. DE proportion); and
- Fuel poverty.

In summary, 3,381[67] of the survey responses from domestic customers were used to produce a training data set of 100,000 sample populations. Each of these sample populations could be defined by values of VoLL indicators, and this data set was used to train a model that is able to predict the value of VoLL for any population for which the VoLL indicators are known. This domestic VoLL model can therefore be used to extrapolate predictions of domestic VoLL outside of the survey population, and indeed has been used make predictions of domestic VoLL across the whole of GB as part of this project.

3.2.4 Domestic and SME VoLL Aggregation

The Impact Research customer survey included 615 valid SME responses[68], on which similar analysis can be performed as the domestic respondents. However, many of the customer attributes collected in the survey are either less relevant for SME customers (e.g. age, fuel poverty) or not publicly reported (e.g. electricity consumption). Industry classification was also collected but there are too many different sectors for meaningful statistical conclusions to be drawn from the analysis. Even at the highest level there are 10 standard industry classification (SIC) codes, and it is necessary to have a sample of more than 200 responses to calculate a VoLL. This would mean that in order to estimate a VoLL for every industry classification you would need at least 2,000 SME survey responses, and certainty that each had accurately provided a valid industry code.

As a result, it is challenging to do any more detailed analysis on SME VoLL other than calculating an urban SME VoLL and a rural SME VoLL. This analysis has already been performed by Impact Research, which concluded a rural SME VoLL of £68,500 and an urban SME VoLL of £44,000[69].

[66] All of the VoLL indicators considered are discussed in more detail in Appendix A2.
[67] Although 5,000 domestic customers were surveyed, it was not possible to use all 5,000 responses in the analysis, as not all customers responded to WTA scenarios specifically associated with unplanned outages. In keeping with the Impact Research methodology, our dataset is therefore comprised of the 3,381 valid responses received for domestic WTA for unplanned outages.
[68] Again, although 1,500 SME customers were surveyed, only 615 responded to WTA scenarios specifically associated with unplanned outages. As with the domestic surveys, we have been consistent with the Impact Research methodology and our dataset is therefore comprised of the 615 responses received for SME WTA unplanned outages.
[69] Several different values are quoted for these figures by Impact Research in their report, but these are the totals that were able to be reproduced.

These constant values have been used to aggregate an overall VoLL for a particular population with a known rurality, number of SME's, domestic population and domestic VoLL (where the domestic VoLL is estimated using the VoLL model). A load-share weighted average is used, as was the method applied by London Economics in their original evaluation of VoLL in 2013. In this instance a weighted average of 74:26 was used for domestic consumption to SME consumption. However, in deriving a more disaggregated model, it is possible to vary this weighting on a population to population basis using consumption estimates for the particular population. The following equation is therefore used to calculate the overall VoLL[70]:

$$VoLL = \frac{VoLL_{SME} \times n_{SME} \times E_{SME}}{(n_{SME} \times E_{SME}) + (n_{domestic} \times E_{domestic})} + \frac{VoLL_{domestic} \times n_{domestic} \times E_{domestic}}{(n_{SME} \times E_{SME}) + (n_{domestic} \times E_{domestic})}$$

This equation is presented in full as it is important to understand the various factors that influence the overall VoLL that is reported for a particular population. Relatively, more effort has been directed in this project towards deriving a disaggregated model for domestic VoLL, but this does not mean that it is the only factor in determining an estimate for the overall VoLL. Other very important factors include accurately estimating:

- SME VoLL;
- Domestic consumption; and
- SME consumption.

3.3 MODEL ACCURACY

Typically, a machine learning model would be evaluated by withholding a portion of the available training data for testing purposes only. This ensures that the model is able to generalise well, and has not been over-fitted to the training data. A challenge with the approach used to create the VoLL model is that even if a portion of the training data is withheld, the 100,000 sample populations have all been created from the same 3,381 survey respondents, and so there is still a danger of over-fitting to the survey results.

As such an alternative approach has been developed for verifying the VoLL model, in which survey responses are withheld before generating the sample populations. 60 different permutations of 250 survey respondents were withheld, and for each permutation 10,000 sample populations were created with the remaining survey respondents. This allowed 60 different models to be trained on 10,000 sample populations each. It meant that each model was able to be tested against a prediction of VoLL for the 250 survey respondents that had been withheld. This is equivalent to testing the model against entirely new survey data for those 250 respondents. A sample of the results for 10 out of the 60 tests is shown in Figure 4.

[70] Where $VoLL_{SME}$ is the SME VoLL, n_{SME} is the number of SMEs in the population, E_{SME} is the average electricity consumption of the SMEs in the population, $VoLL_{domestic}$ is the domestic VoLL, $n_{domestic}$ is the number of domestic households and E_{SME} is the average household electricity consumption of the domestic population.

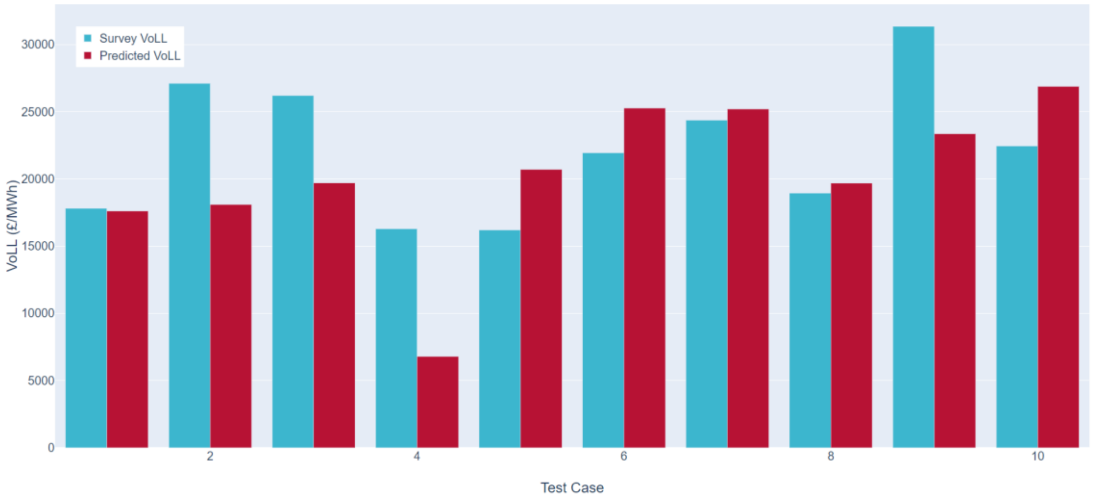

Figure 4: The surveyed VoLL is shown in blue, and the VoLL predicted by the VoLL model is shown next to it in red. The surveyed VoLL is the VoLL determined from a sample of 250 survey respondents. In each case the predicted VoLL is estimated using a model that has been trained on data on which the 250 survey respondents for the 'test' have been removed.

The metric used for quantifying the overall assessed accuracy of the model is the root mean squared error (RMSE). In this case the error is the difference between the model predicted VoLL and the VoLL reported by the survey respondents. The model may over predict or under predict VoLL (as can be seen in Figure 4), and so this error may be positive or negative. Taking the mean of the squared error (and then calculating the square root) ensures that the reported accuracy is always greater than zero and accounts for the absolute error.

The assessed accuracy of the VoLL model has been determined to be an RMSE £6,109/MWh, for the 60 different models for which survey data was withheld. This represents a 29.2% improvement over the current 'vanilla model' employed by Ofgem, in which a fixed value of £16,000/MWh is used across GB. As shown in Figure 5 the Ofgem 'vanilla model' has an RMSE of £8,624 by comparison. Also shown is the error in the instance that a 'vanilla model' using the Electricity North West derived value of £17,481/MWh is employed instead. The RMSE in this instance is £7,667/MWh, and the relative improvement of the VoLL model compared to this is 20.3%.

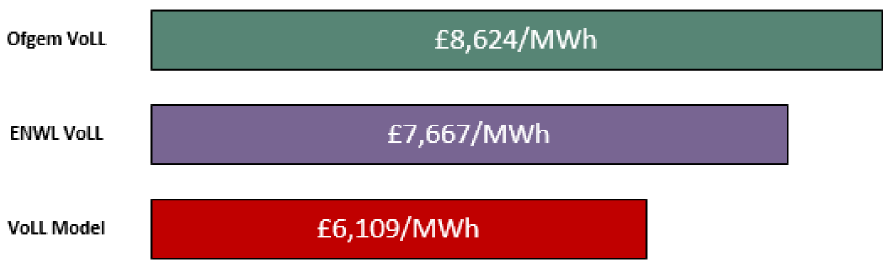

Figure 5: Accuracy of the VoLL model, reported as the RMSE, and compared against two different 'vanilla models' in which a fixed value is for VoLL.

Examining Figure 4 in more detail reveals an instance (test case 4) where the VoLL model significantly under predicts the value of VoLL. In delivering a practical implementation of the VoLL model one consideration might be whether it is prudent to 'cap' the values of VoLL that may be predicted by the model. This would prevent very high or very low values of VoLL being reported in areas in which there are outlying statistics for the VoLL indicators. For instance, if a lower cap of £15,000/MWh and an upper cap of £25,000/MWh was implemented with the current VoLL model then the RMSE would drop to £5,606/MWh (an improvement of 35% against the Ofgem 'vanilla model').

Examining specific test cases also reveals some of the challenges in building a model to predict VoLL. Table 1 shows the main VoLL indicators for validation test cases 19 and 22. Both have very similar indicators, and as a result the model predicts their values of VoLL to be within £600. In reality the results of the survey show that there is more than a £7,000 difference between the VoLLs of these two populations.

ID	Rurality	Mean Income	Mean Consumption	Fuel Poverty	DE	Predicted VoLL	Survey VoLL
19	Urban	£24,657	3,244 kWh	13.6 %	32 %	£20,817/MWh	£19,538/MWh
22	Urban	£25,187	3,496 kWh	12.4 %	34.4 %	£20,235/MWh	£26,992/MWh

Table 1[71]: Predicted VoLL and survey VoLL for test cases 19 and 22, alongside the main VoLL indicators. The VoLL indicators are very similar but the surveyed VoLLs are not.

This example is presented to demonstrate that there is significant variability in the VoLL reported by customers, and that this cannot always be explained by the available statistics for those customers. Of course an additional VoLL indicator may improve the accuracy of the model further but omitting the additional indicators considered in this study (see Annex A2) had the effect of improving model accuracy. The VoLL is, by definition, highly reliant on the preferences and behaviours of individual customers and this introduces significant variability in the values of VoLL that they report.

A histogram of the training errors of the prototype VoLL model is shown in Figure 6. This diagram demonstrates two characteristics of the prototype model:

1. The RMSE is £3,778, which is much lower than the £6,109 observed when testing against withheld data. This demonstrates why testing against withheld data was necessary.
2. Examining the shape of the distribution reveals the wide spread in the errors in the VoLL that is calculated for different populations. Whilst the RMSE is £3,778, this is by definition an average, and on many occasions the error will be much higher than this.

Further work could be completed to further characterise the uncertainty in the VoLL predicted by such a VoLL model. Such statistical analysis should be undertaken on any variable VoLL model that is planned to be introduced to any regulatory mechanisms. The analysis reported in this document presents an overview of the accuracy and uncertainty achieved with the prototype model. It is not a comprehensive analysis but is intended to provide sufficient information to facilitate informed discussion around whether or not further work on a variable VoLL model is required.

[71] EV ownership, vulnerability, off-gas and experience of power cuts are not displayed in the table as they are not included in the most accurate version of the model. However in this case they are also very similar. EV ownership is 6% and 3.6%, vulnerability is 65% and 67% and experience of power cuts is 55% and 50% for test cases 19 and 22 respectively. Off-gas is 24% as opposed to 0.4%, but you would typically expect being off the gas network to raise the VoLL not lower it.

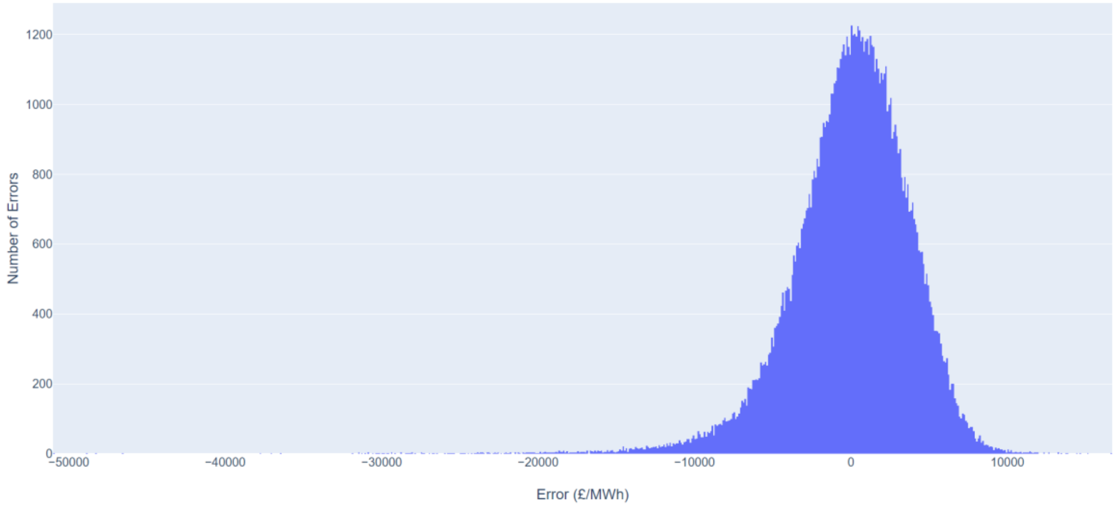

Figure 6: The distribution of the training errors in the prototype model. The RMSE is £3,778/MWh but examining the distribution of errors shows that the error is often much larger than this.

This study demonstrates that it is challenging to develop a model that can account for all of the variability in VoLL. However, it does demonstrate that it is possible to develop a model that reflects some of this variability, and that such a model would be more accurate than a 'vanilla approach'. A variable model can only be applied in practice if 'hard coded' into the regulatory mechanism for RIIO-ED2 and beyond, in common with the manner that the single VoLL is a construct of the RIIO-ED1 framework. As such, it will need to be adopted on an industry wide basis and be agreed by Ofgem. If a model for variable VoLL is taken forward, additional analysis is recommended to further refine the model from the prototype presented here, and to statistically characterise the uncertainty associated with the developed model.

3.4 DATA SOURCES FOR THE PROTOTYPE MODEL AND VOLL VISUALISATION TOOL

As part of this project, the prototype VoLL model was used to predict the VoLL for every Lower Super Output Area (LSOA), in GB. As part of this project, Frazer-Nash have developed a prototype VoLL Visualisation Tool, which displays predictions and allows the user to explore the variations in VoLL across an interactive map of GB, as shown in Figure 7.

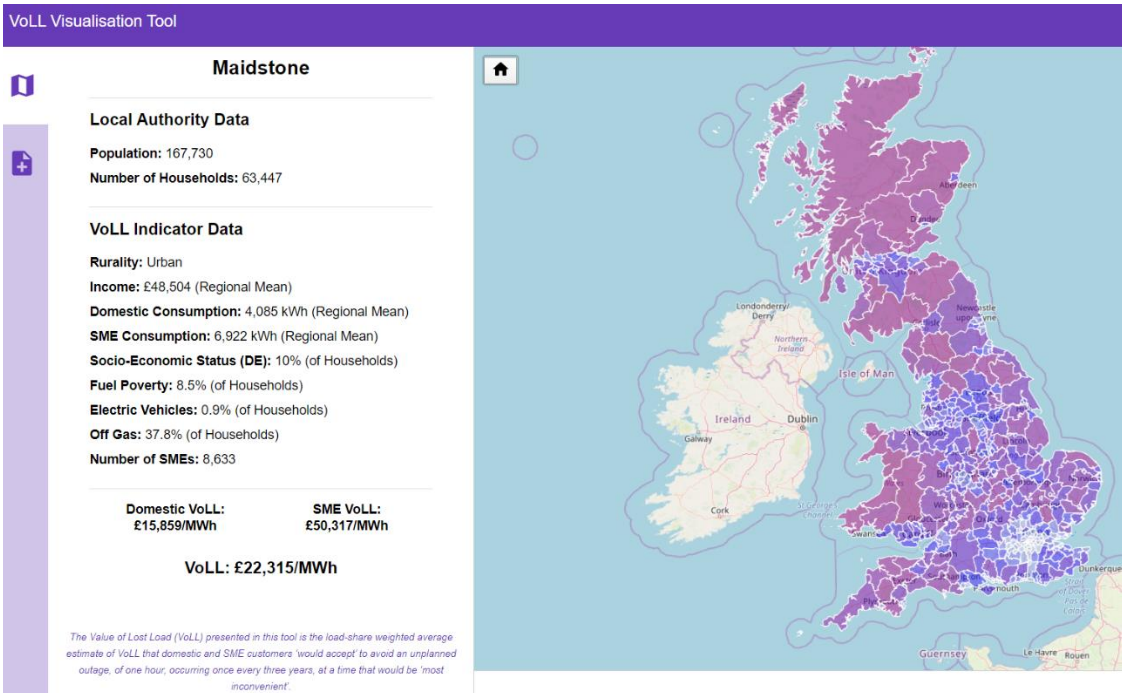

Figure 7: A screenshot of the VoLL Visualisation Tool.

The VoLL indicators used to make the VoLL predictions in this prototype visualisation tool were those established as key drivers of VoLL in the original study. The data sources used to aggregate these indicators to GB level have largely been derived from ONS records. A full description of all the data sources for each indicator, and a discussion of each indicator's impact on model accuracy, is provided in Annex A2.

It should be noted that the accuracy results reported in Section 3.3 are for a version of the domestic model that includes only the following indicators:

- Rurality;
- Income;
- Electricity consumption;
- Socio-economic status (DE); and
- Fuel poverty.

Additional indicators were found to not materially impact the accuracy of the model, and so have been excluded from the analysis at this prototype stage. These indicators include population age, vulnerability, EV ownership, off gas status and previous experience of power cuts.

It is of note that vulnerability and the experience of unplanned power cuts were, in part, omitted from the model because this data was only available for the Electricity North West region. It is however acknowledged that fault history and sensitive priority service register status are likely to be attributes that both Ofgem and individual DNO would wish to see incorporated into a variable VoLL model, specific to their licenced area, even where there are diminishing returns from including these characteristics.

These indicators could easily be included in a future version of the model, should additional analysis suggest that there is merit in doing so, and suitable nationwide sources for the data are available. Indeed EV ownership and off gas status have been included in the current version of the VoLL Visualisation Tool that is available to Electricity North West.

4. DISCUSSION

4.1 RECOMMENDATIONS ON DISAGGREGATION

Ofgem currently recommends that a uniform VoLL of £16,000/MWh is applied by DNO's across GB. There are a number of steps that could be taken in order to improve the accuracy and fairness of the application of VoLL, with the current uniform VoLL considered as the baseline methodology.

Firstly, the Impact Research customer survey commissioned by Electricity North West found that the current Ofgem value is much lower than was suggested by the respondents in the 2016/17 survey. The survey suggests that across Great Britain the average load weighted VoLL for domestic and SME customers is in fact £25,301/MWh. Even if a variable VoLL model is not adopted in RIIO-ED2, updating the set value of the uniform VoLL to nearer this amount would have a significant impact on the accuracy of the VoLL that is applied by DNO's on behalf of their customers and improve the accuracy of estimations by over £9,000/MWh. This is greater than any gains in accuracy that could be expected from applying a model for variable VoLL.

Secondly, a crucial figure in the calculation of a blended domestic and SME VoLL is the ratio of domestic to SME electricity consumption. The ratio used by Electricity North West to reach the figure of £25,301/MWh is 74:26. This was used for parity with the previous London Economics study for Ofgem in 2013. However, the domestic electricity consumption, household, non-domestic electricity consumption and UK business activity data sets from ONS used in this study suggest that the ratio is closer to 83:17. This would mean that the value for VoLL implied by the results of the Electricity North West customer survey is in fact approximately £22,500/MWh. If an updated uniform VoLL is adopted, further investigation is recommended into the ratio that is used for the load-weighted aggregation of domestic and SME VoLL.

There are then a number of options that could be progressed in terms of moving to a variable VoLL model, as was explored in this scope of work. Each of these options offers a solution with a varying degree of complexity. For example, you could maintain the use of constant values for domestic and SME VoLL, but in such a manner that reflects the actual composition of specific areas by taking account the data used for the load-weighted aggregation (i.e. domestic and SME electricity consumption) by location. Analysis of this data suggests that accuracy would be improved by approximately £2,000/MWh by using such a disaggregated load-aggregation methodology. It would also not be a significant further step to apply such an approach, but to use different constant values for domestic and SME VoLL in urban and rural areas. Instead of two constant values of VoLL (domestic and SME), there would be four (domestic urban, domestic rural, SME urban, SME rural). Analysis of the data suggests that this would improve the accuracy of estimations by a further £1,000/MWh, in comparison to using a uniform VoLL based on the Electricity North West value.

Further improvements would then need to come from using a fully disaggregated model for either domestic or SME VoLL, using VoLL indicators such as income, fuel poverty and electricity consumption. An example of such a model has been established for domestic VoLL in this project, and is described in Section 3. The analysis presented in Section 3.3 suggests that the capped domestic model achieves an accuracy of £5,606/MWh, which is approximately £1000/MWh better than using fixed values for urban and rural domestic VoLL. It is possible that this accuracy might be improved further with additional research. Such research might need to involve more customer surveys and would benefit from a joint DNO collaborative approach. Although 5,000 domestic customers were surveyed, the VoLL estimated was based only on the survey population that responded to WTA scenarios, specifically associated with planned interruptions. Once these responses had been extracted, this smaller sample was subsequently split by rurality and invalid responses were removed. This often left a sample of only a few hundred responses, or less, for some VoLL indicators. Ideally you would train the model using larger, more stable sample populations (i.e. greater than 250 in size) but the available volume of data does not allow for it.

A model for variable SME VoLL has not been fully explored in this project, as discussed in Section 3.2.4. Further improvements in accuracy could be achieved by developing an accurate variable model for SME VoLL, although the effect of these improvements will be reduced by the fact that SME VoLL only accounts for between 15-25% of the overall blended VoLL (depending on which ratio you use).

Statistical analysis should be performed on any fully disaggregated models that are implemented for either domestic or SME VoLL. This should include not just analysis of model accuracy (as presented in this report for the prototype model), but also on bounding the uncertainty associated with VoLL predictions made using such models.

4.2 RECOMMENDATIONS ON GEOGRAPHIC GRANULARITY

The implementation of a model for variable VoLL, must also consider the granularity of the geographic data used to derive it. The level of accuracy of a variable VoLL model is unlikely to be so great that input data is necessary at a finer level of detail than LSOA. As such data is readily available in most cases for the required inputs, this seems to be an appropriate level of granularity to use.

It is however acknowledged that the fundamental argument for a variable model is the ability to calculate the VoLL for a particular distribution or network asset. This could be achieved by calculating the VoLL at LSOA level, and simply applying the LSOA VoLL to all assets that sit within it. However, it is recognised that electricity networks are not aligned to LSOAs and this introduces geospatial complexities in the calculation of VoLL when assets serve customers across multiple LSOA's. In these circumstances, to more fairly aggregate the VoLL, it would be necessary to either:

a) Select an asset area using a variable VoLL calculation tool. The example shown in Figure 8 demonstrates how this could be achieved by implementing a web application that includes point and click functionality to select an area, either as a point and radius or via drawing a freeform polygon. This would apply a load-weighted aggregation to the VoLLs for the households and SMEs in the area; or

b) Use network connection databases to determine exactly which households and businesses are served by an asset, and then apply a load-weighted aggregation in a similar way.

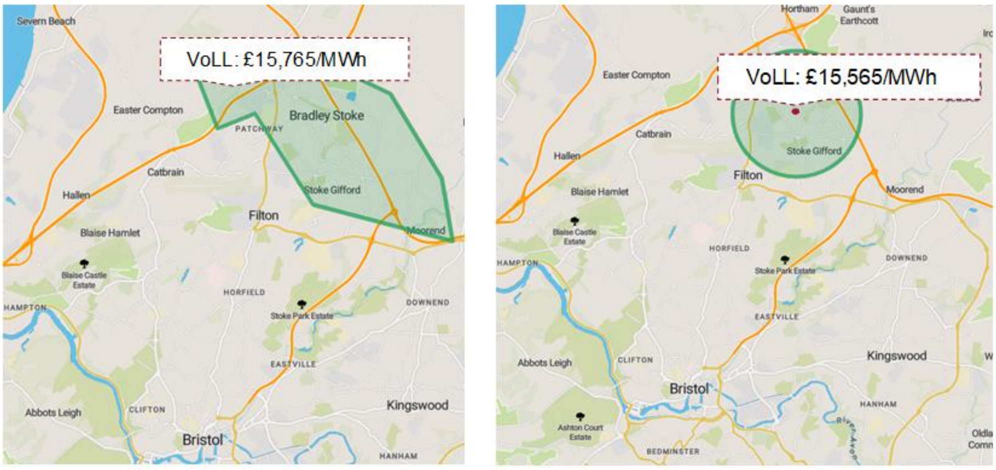

Figure 8: An example of how you might select an area served by an asset in a variable VoLL calculation tool. This could be by selecting a point and radius (as on the right) or by drawing a freeform polygon (as on the left).

However the more complex the variable VoLL model that is implemented, the greater the volume of input data that will be required. This in turn will increase the requirement and complexity of maintaining and updating these data sets. Careful consideration should therefore be given in the relative advantages and costs of the various models for variable VoLL.

4.3 IMPLICATIONS OF A VARIABLE VOLL ON PRICE CONTROL REGULATION AND INVESTMENT DECISION MAKING

The implications of a variable VoLL on price control regulation and investment decision making were discussed at a workshop hosted by Electricity North West in October 2019, attended by representatives of each of the DNO's and Ofgem. The following section summarises the main themes and arguments raised during this discussion.

4.3.1 Variable VoLL Workshop Discussion (October 2019)

Electricity North West propose that a practical variable VoLL methodology should not involve a significant change in the way that DNOs assess the benefits of lost load mitigation, but provide an opportunity for DNOs to refine existing models to produce a more precise method for prioritising investment strategies. This approach introduces a new dimension of sophistication by adding a customer dimension, which focuses on the impact of those decisions, but does not drastically alter the current process or difficulty.

Currently the CBA and CNAIM methodologies lend themselves to a variable VoLL. For example, extending the base CBA engine, by replacing the fixed VoLL perimeter with a range of alternate factors, more attuned to the benefits of customers served by the asset, will inform more efficient investment decisions. The same principal applies to the assessment of costs when considering the failure of assets in the CNAIM. There would be little difficulty introducing a variable VoLL into the common methodology, but it is recognised that the model must be simple to administer.

The prototype VoLL model developed from the analysis documented in the report is beneficial for DNOs and the regulator alike, for not only allowing swift comparison but also to minimise and eliminate modelling and calculation. Consistency and alignment with HM Treasury Green Book processes in calculation methodologies—through a clear and refined best practice guidance—will especially enhance cost benefit analysis processes and investment business case applications.

In theory, greater granularity will provide more flexibility and precision, but there appears to be a limiting factor since DNOs would not be able to utilise individual household data within a RIIO-ED2 variable VoLL implementation. Currently, low voltage circuit level (feeder) is the lowest point at which investment decisions are made—and therefore it is logical for this to be the lowest level of connectivity at which VoLL is modelled. Household granularity information raises complex issues concerning data security protection, assurance and maintaining customer anonymity. Furthermore, should the dataset ever be available in the public domain, the assigned VoLL values of individual households, SMEs and businesses are likely to be challenged.

The existence and availability of future forecasting data sets means that trends in VoLL indicators could be applied to a variable VoLL model to more accurately reflect the whole life and through life VoLL of an asset. For example, within increasing penetrations of LCTs in a future zero carbon scenario. However, there are currently many uncertainties about the general uptake of LCTs and regional patterns of adoption are particularly challenging to predict. Future uncertainties are modelled against a range of assumptions underlying a number of scenarios. However, the details of any forecasting models, including where such forecasting should be applied would need to be commonly agreed prior to RIIO-ED3 implementation. The level of forecasting would need to be explored to ascertain the most efficient and practical way to add-value to making investment decisions, acknowledging that all forecasting below the primary level is highly speculative.

For instance, when considering where forecasting should be applied, the CBA tool and CNAIM respectively consider the benefits and risks of an investment decision across the lifespan of an asset. As a consequence a VoLL forecast through time introduces an improved level of accuracy in the overall assessment. However, the IIS is concerned with rewarding and penalising DNOs in the present. Whilst for the CBA consistency should be key for comparison, and since all CBA projects are submitted in the same price control period they need to be based on comparable datasets. A possible solution could be that a VoLL ‘base year’ is denoted at the start of the price control and all options are indexed from this. This leads to further implementation challenges, and whether separate VoLL values should be created for IIS, CNAIM & CBA. Furthermore, a challenge on implementation’s critical path is whether the VoLL for assets used in the CNAIM methodology can be calculated and verified in time for ED2.

The key challenge currently faced is what timescales should be aimed for to implement a variable VoLL, and whether a short-term and long-term solution is the most relevant reality, considering the ongoing decarbonisation and increasingly mixed electricity generation. DNOs are in the early stages of consultation with Ofgem on the approach to setting the next electricity distribution price control (RIIO-ED2), which starts in April 2023, and the development of their respective business plans. It is acknowledged that within the constrained timescales, introducing a variable VoLL for RIIO-ED2 will need to be simple to use and require minimal ‘bedding in’ time, allowing DNOs to format the components of their business plans with ease. It is recognised, that at this stage, an early iteration of a variable VoLL methodology could be trialled within RIIO-ED2 with the view of perfecting a practical methodology for RIIO-ED3. This approach would provide sufficient time for additional research to refine the model, as recommended in this document.

A trial would also benefit from expected improvements in the accuracy of future electricity scenarios and forecasting models, based on uptake in ED2, as GB transitions towards a decarbonised, decentralised and digitalised future. A variable VoLL trial, in collaboration with other DNOs, is recommended to jointly agree the proposed model should be adapted and developed for RIIO-ED3. This approach would credibly test whether logical 'good decisions' are appropriate across the whole regulatory framework and deliver economically efficient investment decisions within business case proposals.

For instance, there is potential for a variable VoLL to drive the wrong behaviour within the IIS mechanism, which incentivises DNO to improve performance where it is most economically appropriate to do so. Therefore, as an example, a variable VoLL could theoretically disadvantage customers on underperforming networks, who tend to have lower expectations of supply reliability and as a consequence, a lower VoLL. This could lead to the prioritisation of investments in the wrong areas and worsen the divide between worst served customers and those who value security of supply greatest, i.e. early adopters of LCT.

The above highlights the need for industry stakeholders to consider how VoLL is applied within a worst served customer mechanism for RIIO-ED2. In ED1, DNOs have a use-it-or-lose-it allowance to improve network reliability for customers who have a significantly worse than average service, evaluated against specified qualification criteria. The worst served customer regime is a complex approach, which acts as a counterweight to the IIS. Whilst VoLL is not explicitly part of the evidence required to receive funding under this regime, it is implied as part of the financial determinants contained within the mechanism. It is of note that the worst served customer regime also recognises a need for DNOs to treat certain customer groups differently to deliver improvements in service, where customer and network performance benefits outweigh investment costs, but are unlikely to be reflected in a CBA. This acknowledgment provides early justification for a variable VoLL, which reflects the differing needs and impacts of certain customer groups.

The ultimate objective of a variable VoLL trial should be to determine whether resultant decisions better reflect consumers, provide increased consumer benefits and reduce the inefficiencies that exist within RIIO-1. For instance, VoLL trials working in parallel with the day-to-day RIIO-ED2 calculations utilising an updated single VoLL, would allow each variable VoLL methodology for CNAIM, CBA and IIS to be perfected, balancing ease of use with improvement. Alternatively, a variable VoLL could be used by DNOs to test hypothetical or previous CBA investment decisions in order to refine the methodology and application.

5. CONCLUSIONS

The survey conducted by Impact Research on behalf of Electricity North West suggests that VoLL is significantly higher than the current uniform value. The most effective single action that could be taken to improve the accuracy, and thus the fairness, of VoLL in investment decisions across GB is to update the current uniform 'value'. If this simple approach is adopted for RIIO-ED2, consideration should be given as to whether the current assumption for the ratio of domestic to SME electricity consumption in GB is still appropriate.

There are benefits to be gained from the implementation of a variable VoLL model, and many of these benefits could be realised in the application of a relatively simple disaggregated model, which utilises a limited number of attributes, identified as the key characteristics influencing VoLL in this study. Such a model provides a means of disaggregating the load-weighted sum of fixed values for urban and rural/ domestic and SME VoLL. The analysis contained in this report concludes that such a model would improve the accuracy of VoLL estimations by approximately £3,000/MWh over a uniform VoLL.

A more complex variable VoLL model could improve the accuracy of VoLL estimations by around £1,000/MWh, if the prototype developed in this study was implemented. Further research into models for either the domestic or SME VoLL may yield a better model that improves on this further.

Furthermore, whilst including fault history and vulnerability data (specifically the penetration of households on the Priority Service Register (PSR)) may not increase a model's accuracy by a significant order of magnitude, it is nonetheless recognised that inclusion of this data is likely to be attractive to both Ofgem and DNOs as fundamental parameters reflective of need. However, learning derived from this study suggests that adding fault history into the model would require additional analysis, to explore if alternative models trained with different sample populations are able to make better predictions using outage data and this would benefit from a collaborative joint DNO approach which considers accurate fault data across GB.

A more complex model will however incur additional overheads in model and data maintenance, and such considerations could be significant in determining the most appropriate objective for a re-evaluated VoLL.

The aim of any variable VoLL model should be to deliver improvements in the accuracy and fairness of the various applications of VoLL versus the existing single value approach, used within the RIIO-ED1 methodology. Based on the outputs of this analysis it is concluded that introducing a variable VoLL into the current regulatory framework, specifically the CNAIM and CBA methodologies, should deliver significant improvements in accuracy. However, a cautionary approach should be taken in the implementation of any solution, particularly in ensuring that there is a thorough understanding of the statistical uncertainties associated with model predictions. A balance must be found between the accuracy of the VoLL model, the complexity of methodology and how it can be practically implemented to the existing regulatory frameworks for RIIO-ED2 and beyond.

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ANNEX A - DEFAULT

A.1 MODELING ASSUMPTIONS TABLE

Assumptions for Model	
Impact Research Survey	▸ Only VoLL attributes collected in the Impact Research customer survey have been considered as candidate VoLL Indicators ▸ The Impact Research customer survey contained a representative sample of the UK population ▸ Estimates of VoLL derived from the Impact Research customer survey are 'correct'
Independent Coefficients	▸ The model coefficients calculated for individual survey respondents using Hierarchical Bayes techniques are independent and can be used to derive VoLL estimates for sample populations (this is a statistical assumption, but common practice)
Estimates of VoLL	▸ Estimates of VoLL do not account for businesses with 250+ employees, or industrial & commercial (I&C) customers ▸ Estimates of VoLL are adjusted for low income customers, based on the principle that the value of an additional pound of income may be higher for a low income recipient than a high income recipient (the same assumption was made by Impact Research in their analysis)
Load-share weighted average	▸ Overall VoLL is calculated as a load-share weighted average across domestic and SME customers (the same assumption was made by both Impact Research and London Economics)

A.2 DATA SOURCES FOR PROTOTYPE MODEL AND VOLL VISUALISATION TOOL

A.2.1.1 Demographics (Population, Age)

The Impact Research customer survey catalogued ages of respondents in the categories of 18-29, 30-44, 45-59 and 60+. Each sample population in our analysis was subsequently categorised by defining the proportion of the respondents that fell into each age category. This results in four different VoLL indicators, the proportion of the adult population in each age category respectively.

Demographic data is provided annually by the Office for National Statistics (ONS). The Small Area Population Estimate (SAPE) dataset gives estimates of the population by age for every LSOA in GB. The domestic population for each LSOA was recorded as the total population in the LSOA according to the SAPE dataset. The age VoLL indicators were calculated for each LSOA as the sum of the population in the age category, divided by the total population across all the adult age categories.

The population data is used in the prototype VoLL model in order to calculate the load-weighted average of the domestic VoLL and SME VoLL in each LSOA. The age data was excluded from the prototype VoLL model as it reduced the accuracy to £6,214/MWh as opposed to £6,109/MWh without including it as a VoLL indicator.

A.2.1.2 Rurality

Rurality data is provided at an LSOA level by ONS via the Open Geography Portal. The data was last updated following the 2011 census. The following categories are used:

- Urban Major Conurbation;
- Urban Minor Conurbation;
- Urban City and Town;
- Urban City and Town in Sparse Setting;
- Rural Town and Fringe;
- Rural Town and Fringe in a Sparse Setting;
- Rural Village and Dispersed; and
- Rural Village and Dispersed in a Spare Setting.

The prototype model uses just two classifications, rural and urban, and each LSOA is classified via a look-up that identifies whether or not it falls into a broadly urban (i.e. one of the first four) or broadly rural (i.e. one of the last four) category. The developed approach to calculate domestic VoLL uses a separate linear model for urban and rural populations respectively.

A.2.1.3 Income

The Impact Research customer survey catalogued the income of respondents in income bands. In order to calculate a continuous income variable for a sample population when training the model it was assumed that the income of each respondent was in the middle of the recorded income band.

Small area household income estimates are provided for England and Wales at a Middle Super Output Area (MSOA) level by ONS. The data was last updated in 2018. For the VoLL

Visualisation Tool the assumption was made that the income is constant across MSOA's (there are approximately five LSOA's within each MSOA).

LSOA level household income estimates are provided for Scotland by the Scottish Government (statistics.gov.scot). The data was last updated in 2018. Six LSOA's (or 'data zones') were found to be missing in this data set. Leuchars and Guardbridge, Lossiemouth West, Bridge of Allan and University and Garelochhead were all assumed to have the median of the mean LSOA Scottish household incomes, £33,800. Petershill and Sighthill were both assumed to have zero income as they have zero population.

Mean income is used as a VoLL indicator in the prototype model for domestic VoLL.

A.2.1.4 Socio-Economic Status

Approximated social grade data is available at an LSOA level from ONS via Nomis, a data portal for official labour market statistics. This is based on 2011 census data and a method developed by the Market Research Society. For the prototype model the percentage of each LSOA that falls into the 'DE' social grade as compared to the other social grades is used as a VoLL indicator. This grade consists of unskilled manual labourers, pensioners and the unemployed.

A.2.1.5 Electricity Consumption

The Impact Research customer survey catalogued the electricity consumption of respondents in consumption bands. In order to calculate a continuous consumption variable for a sample population when training the model it was assumed that the consumption of each respondent was in the middle of the recorded consumption band.

Domestic electricity consumption is published by ONS at LSOA level. Figures are provided for the mean household electricity consumption for each LSOA in Great Britain. The data was last updated in 2019. Mean electricity consumption is used as a VoLL indicator in the prototype domestic VoLL model. It is also used to calculate the load-weighted aggregation of domestic and SME VoLL. Total domestic electricity consumption for an LSOA is calculated as the number of households in the LSOA multiplied by the LSOA's mean domestic electricity consumption.

Non-domestic electricity consumption is published by ONS at an MSOA level. The data was last updated in 2019. For the VoLL Visualisation Tool the assumption was made that the non-domestic electricity consumption is constant across MSOA's. Non-domestic electricity consumption is used to calculate the load-weighted aggregation of domestic and SME VoLL. Total SME electricity consumption is calculated as the number of SME's in the LSOA multiplied by the LSOA's mean non-domestic electricity consumption.

A.2.1.6 Fuel Poverty

Fuel poverty statistics are provided in England at an LSOA level by the ONS, and were last published in 2019.

For Scotland, fuel poverty statistics have only been published at a Local Authority level, as part of the Scottish Household Condition Survey (SHCS). These were last published in 2018, and it is worth noting that fuel poverty was not included in the 2019 SHCS. For the VoLL Visualisation Tool it was assumed that fuel poverty is constant across local authorities in Scotland. The number of LSOA's in a local authority varies significantly, with 29 in the Orkney Islands and 746 in Glasgow City.

For Wales local authority fuel poverty estimates were provided in 2016 on the gov.wales website, with an overall fuel poverty of 23%. The 2018 fuel poverty report did not provide a disaggregation by local authority, but did report a decrease in overall fuel poverty to 12%. The

2016 local authority figures were therefore scaled by a 12:23 ratio in order to include local authority fuel poverty estimates in the VoLL Visualisation Tool. The 2016 figures were banded, and so it was assumed that the fuel poverty in each local authority was in the middle of the reported band.

Fuel poverty is used as a VoLL indicator in the prototype model for domestic VoLL.

A.2.1.7 Off-Gas

A database of postcodes that have no record of a gas connection is maintained by Xoserve, the Central Data Service Provider (CDSP) for the gas industry. The list of off-gas postcodes was last published in 2019. For the VoLL Visualisation Tool this list was used to determine the number of postcodes that are off the gas network in each LSOA. To calculate a proportion of households that are off the gas network the simplifying assumption was made that there are 43 households in each GB post code (the GB average). The number of off-gas postcodes was therefore multiplied by 43 and divided by the number of households in the LSOA to get the proportion of households off-gas in an LSOA. This figure was capped at 100% in the instance that the calculation returned a result greater than 100%.

It would be possible to calculate a more accurate estimate by determining the actual number of properties for every postcode in each LSOA and calculating the proportion of off-gas postcodes directly. It is recommended that these calculations are performed should off-gas be used as a VoLL indicator in a future version of the VoLL model.

However, for the prototype model for domestic VoLL off-gas is not used as a VoLL indicator. It was excluded from the prototype VoLL model as it reduced the accuracy to £6,211/MWh as opposed to £6,109/MWh without including it as a VoLL indicator.

A.2.1.8 Electric Vehicle Ownership

Electric vehicle (EV) ownership statistics are not publicly available without a specific request to the Driving and Vehicle Licensing Agency (DVLA). Instead, for the purpose of investigating the appropriateness of EV ownership as a VoLL indicator, EV charge point locations were used as a proxy for ownership in a region.

Open Charge Map is the global public registry of EV charging points. Data is sourced from a variety of databases and services, in addition to being ‘crowd sourced’ directly from users themselves. As of November 2019, there were 20340 charging stations at 7792 locations recorded in the UK. These locations were aggregated at a local authority level to determine the number of charging point locations in each local authority area[72].

EV ownership estimates were provided for the project by Electricity North West for their North West region. Its current best estimate is 11399 EVs in the North West region in 2019. Open charge map suggests that there are currently 270 charge point locations in this region. A multiplier of 11399 / 270 = 42.2 was therefore used to estimate the number of EVs in each Local Authority from the number of charge point locations. The number of EVs in each LSOA was then estimated by distributing the estimated number in each local authority amongst the LSOA’s in their area, weighted by the population of the LSOA. Finally, the proportion of households that own EVs was calculated as the estimated number of EVs in each LSOA divided by the number of households.

[72] Initial aggregations were performed at an LSOA level, but this resulted in many LSOA’s with zero EVs. Therefore, the aggregation was performed by local authority instead and then EV ownership distributed amongst LSOA’s by population.

It was concluded however that for the prototype model EV ownership would not be used as a VoLL indicator. It has been excluded from the prototype VoLL model as it reduced the accuracy to £6,378/MWh as opposed to £6,109/MWh without including it as a VoLL indicator.

Figure 9 demonstrates why the prototype model has been unable to identify any clear patterns in the correlation between EV ownership and VoLL. From the scatter plot of EV ownership against VoLL for the urban training data set there is no clear identifiable trend between the two variables. This does contrast with the Impact Research finding that EV owners tend to have a 25% higher VoLL. However, this analysis was essentially for a 100% EV owning population, and there was not a large enough volume of training data from the customer survey to create such a population. Once customers who have not seen unplanned outages are removed[73], there are only 182 urban EV owners and 89 rural EV owners in the survey data set. In creating sample populations including 250 respondents each, it is not possible to produce a sample population with anything higher than 73% or 36% EV ownership for the urban and rural models respectively. As seen in Figure 9, at this rate of ownership, there is no correlation with VoLL.

More data is required to further investigate the relationship between EV ownership and VoLL using this methodology. Specifically additional domestic EV owners should be surveyed such that there are at least 250 urban and 250 rural EV owners in the survey data set.

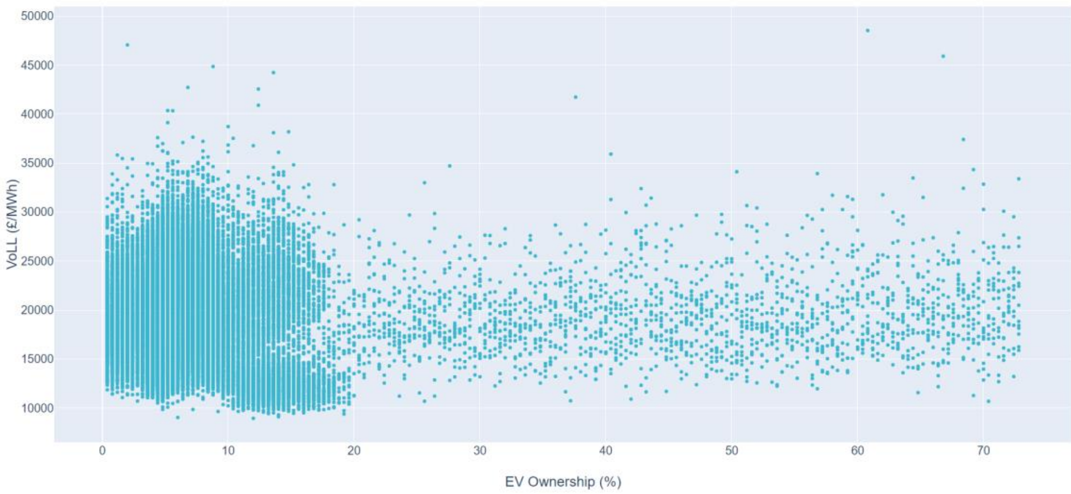

Figure 9: EV ownership compared to VoLL for the sample populations in the urban training data set.

A.2.1.9 SME Counts

SME counts are provided by local authority in the ONS UK business activity data set. This data set catalogues the 'local units' (i.e. places of work) using VAT trader and PAYE information. It details local units by employment size band, allowing the SME count to be retrieved as the number of units employing less than 250 people.

In order to estimate the number of SME's in each LSOA, the SME count for each local authority was spread over the LSOA's in the local authority, weighted by LSOA population. The assumption that enterprise locations are correlated to population centres is thought to be appropriate for the prototype VoLL model, but any future model development should consider if a more granular source for SME location data can be found. This could be achieved using connectivity data, specifically profile classification data associated with Meter Point

[73] In keeping with the Impact Research methodology.

Administration Numbers. However, this would introduce greater complexity in maintaining and updating the model to reflect changes in the source data.

The SME count is used to calculate the load-weighted aggregation of domestic and SME VoLL. Total SME electricity consumption is calculated as the number of SME's in the LSOA multiplied by the LSOA's mean non-domestic electricity consumption.

A.2.1.10 Experience of Power Cuts

The Impact Research customer survey included questions to establish if the respondent had experience of a planned or unplanned power cut. This allowed analysis to be undertaken as to whether or not including the proportion of a sample population that have experienced an unplanned power cut is a significant VoLL indicator. This analysis showed that including it as a VoLL indicator in the prototype variable model reduced the accuracy to £6,156/MWh as opposed to £6,109/MWh without including it as a VoLL indicator.

Experience of unplanned power cuts has not been included as a VoLL indicator in the prototype variable VoLL model. This decision was, in part, because the VoLL Visualisation Tool was developed to demonstrate VoLL estimates across the whole of GB, and fault data was only available for the Electricity North West region. The other reason was due to the analysis showing that including experience of unplanned power cuts as a VoLL indicator did not improve the accuracy of the model. Additional analysis could be conducted to explore if alternative models trained with different sample populations are able to make better predictions using fault history data. However as described, the initial analysis did not suggest that it would yield significant improvements in model accuracy and as GB-wide fault data was not available for the prototype model, such analysis has not been conducted as part of this study.

A.2.1.11 Vulnerability

Whether or not a customer is classified as vulnerable was also captured by the customer survey data. This allowed analysis to be undertaken as to the effectiveness of including vulnerability is a significant VoLL indicator. This analysis showed that including vulnerability as a VoLL indicator in the prototype VoLL model resulted in a slight increase in accuracy to £6,047/MWh as opposed to £6,109/MWh without including it.

Vulnerability has not been included as a VoLL indicator in the prototype VoLL model and the reason for this was twofold. Firstly, vulnerability data, which is classified as personal and highly sensitive, cannot be distributed freely without consideration for General Data Protection Regulation (GDPR). As such, PSR data held by Electricity North West was not available to Frazer Nash for the prototype model build. Secondly, the analysis revealed that vulnerability as a VoLL indicator only slightly improved the accuracy of the model (representing a 29.9% improvement as compared to a 29.2% improvement). Additional analysis could be conducted to explore if alternative models trained with different sample populations are able to make better predictions using customer vulnerability data. However, the initial analysis did not indicate that it would yield significant improvements in model accuracy. As vulnerability data for Electricity North West's customer base and for other licenced DNOs was unavailable for the prototype model, such analysis has not been conducted as part of this study.

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