Armagh Upgrade

Needs Report

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Summary

The distribution network supporting the demand in Armagh is supplied from the 110/33 kV transmission substation (or bulk supply point (BSP)) at Drumnakelly Main. With increasing uptake in low carbon technologies and demand growth associated with Electric vehicles (EVs) and heat pumps the forecasted demand in the Armagh area will exceed the firm capacity of the 110/33 kV transformers at Drumnakelly substation. Additionally, it has been determined that based on the forecasted peak demand for a winter peak day at Drumnakelly Main, whilst exceeding the 90 MVA nominal rating of the transformers, the site would be within the cyclic overload rating of the transformers up to about 2032.

Beyond 2032, to maintain compliance with the Transmission and Distribution System Security and Planning Standards (TSSPS and DSSPS), and to manage the demand in fault conditions, a post fault demand transfer onto Waringstown Main will be required until the second transformer is restored. This would result in the 33 kV system operating radially at this time, and if that radial operation was prolonged there could be further risk to supplies. To prevent overload prior to the demand transfer taking place the automatic disconnection of load may be required. Whilst an arrangement like this needs to be considered it is unlikely to ever be required because transformer faults are rare, and this would need to occur at peak demand in Winter. However, this is not sustainable long term as it provides no capacity for future load growth.

NIE Networks has identified that at times of high electrical demand in the Armagh area, the firm capacity of the 33 kV distribution network is exceeded. For the loss of one of the four 33 kV circuits from Drumnakelly that supply the Armagh distribution system (N-1 contingency) the remaining 33 kV circuits are at risk of overload and can exceed statutory voltage limits. Value of Lost Load (VoLL) analysis has been used to financially assess the impact of future potential faults, planned maintenance outages and normal system operation (NSO) on the 33 kV network supplying the Armagh area. The overall total cost of VoLL from faults, maintenance and during normal system operation from 2024-2064 is estimated to be £258.93m.

This report, which has been prepared jointly by NIE Networks as Distribution Network Owner (DNO) and SONI, sets out the case of need for reinforcing the distribution and transmission network at Armagh and Drumnakelly.

1 Introduction

Two separate needs have been identified regarding the security of supply of the 33 kV distribution system supplying the Armagh area and capacity upstream at Drumnakelly Main substation which also supplies the Portadown and Craigavon areas.

For the loss of one of the four 33 kV circuits from Drumnakelly that supply the Armagh distribution system (N-1 contingency) the remaining 33 kV circuits are at risk of overload and can exceed statutory voltage limits.

At peak times the demand at Drumnakelly Main is in future expected to exceed the nominal rating of the transformers. This remains below the estimated cyclic overload rating of the transformers up to 2032. However, after 2032 the forecasted demand exceeds this rating and a post fault demand transfer to Waringstown would be required to ensure the site remains compliant with the Transmission and Distribution System Security and Planning Standards (TSSPS and DSSPS). This would also require the automatic disconnection of load until the transfer takes place to avoid thermally overloading the remaining in-service transformer. This is not expected to be sustainable long term as it provides no capacity for future load growth and by operating the 33 kV system radially there is an increased risk to supplies if a secondary failure took place.

With forecasted demand figures likely to make the occurrence of these issues more prominent, it is necessary to reinforce the transmission and distribution network supplying Armagh to ensure compliance with the TSSPS and DSSPS. This report documents this need.

2 Description of the network

2.1 Drumnakelly Main

Drumnakelly Main 110/33 kV substation was established in the 1960s. Located on the outskirts of Portadown, this transmission substation supplies a 33 kV distribution system which in turn provides power to approximately 46,000 customers. In addition to Portadown, the substation supplies the town of Craigavon, as well as industrial estates at Seagoe and Carn via a 33 kV underground cable network. The substation also provides supply to the city of Armagh and rural towns including Benburb, Keady, Killylea, Markethill, Richhill and Tullygoonigan via four parallel operated 33 kV overhead lines.

The substation comprises an eight bay 110 kV air insulated switchgear (AIS) mesh, which was rebuilt in 1998, and includes one unequipped spare bay. The substation comprises two 90 MVA 110/33 kV transformers and a sixteen panel 2,000 A double busbar 33 kV switchboard (including a bus section and coupler breakers). The substation is connected to the 110 kV network via two circuits to Tamnamore substation and three circuits to Tandragee substation. The substation is within a site, shown in Figure 1, which is heavily constrained in terms of the scope for expansion.

Figure 1 - Drumnakelly Main Substation

2.2 Armagh Distribution Network

Armagh city and the surrounding rural area is supplied from Drumnakelly Main via four 33 kV circuits (a combined total of 138 km of overhead line) operating in parallel. These circuits bring supply to eight 33/11 kV primary substations, including two substations that supply Armagh city, shown below in Figure 2. The two central 33 kV circuits (shaded in Figure 2) are constructed with 200 mm^2 conductor. These circuits are supported by a further two lower capacity circuits feeding the area through 33/11 kV substations in Richhill and Markethill. Network security is maintained based on three out of the four circuits remaining operational at all times.

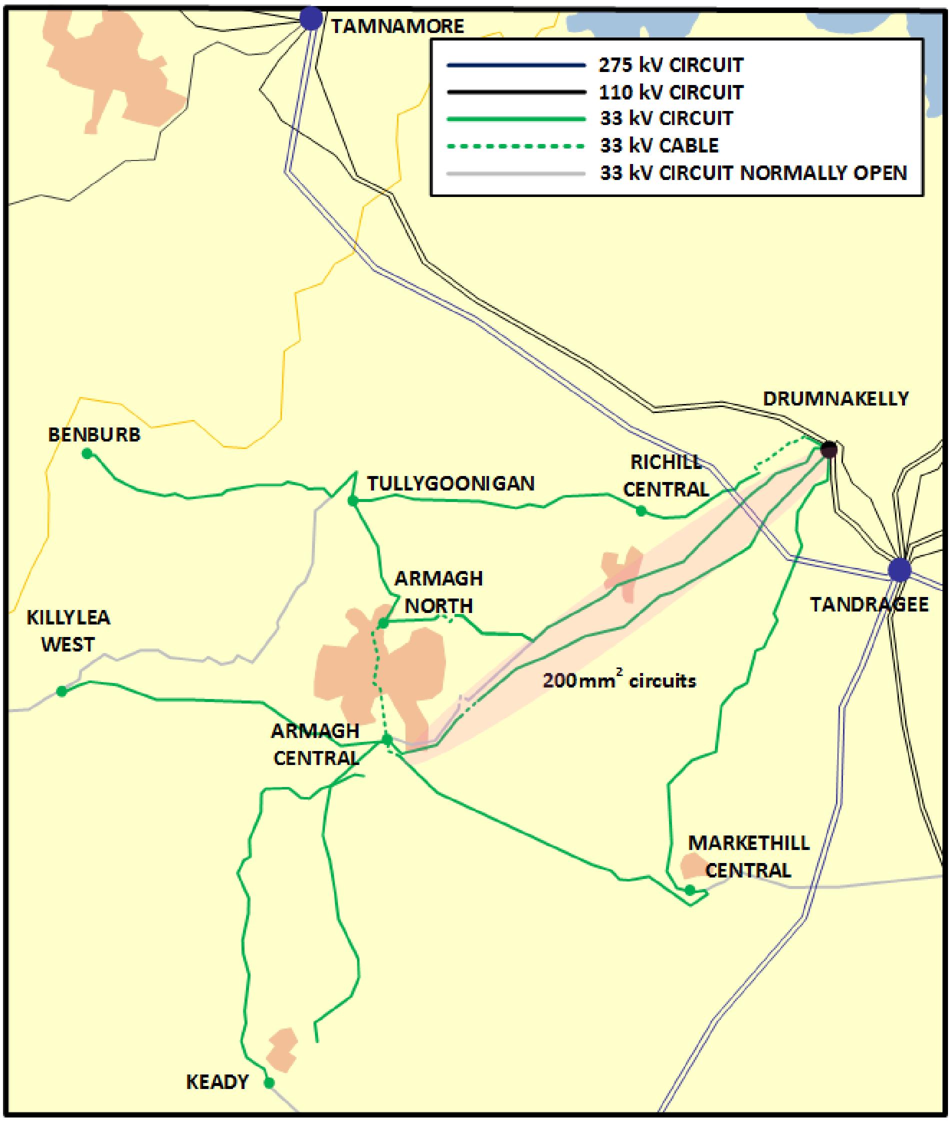

Figure 2 - Distribution network in Armagh area

3 General Network Issues

Issues have been identified at both Drumnakelly Main 110/33 kV substation and on the 33 kV distribution network supplying the Armagh area. The issues are driven by the level of demand in the area and the firm capacity at Drumnakelly Main and the 33 kV circuits supplying the Armagh network area.

A N-1 contingency of one of the four 33 kV circuits supplying the Armagh area can lead to potential voltage excursions outside of statutory limits. The demand at Drumnakelly Main is also expected to approach firm capacity, although there is significant post fault transfer capacity.

Electricity demand is forecast to increase significantly due to electrification in all sectors of the economy. This is as per the Climate Change Act (Northern Ireland) 2022.

For the analysis described in this report a demand forecast for Drumnakelly has been derived to 2032/33 from NIE Networks' transmission demand forecast. This was produced by NIE Networks in 2024 from study year 2022/23. Forecasted peak demands represented in this analysis are derived from 2023/24 onwards.

3.1 Demand at Drumnakelly

Table 1 below sets out the present and forecast peak demand on Drumnakelly Main substation.

Year	2022 /23	2023 /24	2024 /25	2025 /26	2026 /27	2027 /28	2028 /29	2029 /30	2030 /31	2031 /32	2032 /33
Demand (MVA)	88.74	89.41	90.54	91.51	92.37	93.29	94.31	95.83	97.78	100.54	103.21

Table 1 - Present and Forecast demand at Drumnakelly

Table 1 shows the maximum demand at Drumnakelly Main is forecasted to exceed the 90 MVA nominal rating of each 110/33 kV transformer and continue to increase with increasing forecasted peak demands. With the future electrification of heat and transport the maximum demand is expected to increase more rapidly as improving technology and government legislation changes drive more people to adopt electric vehicles and heat pumps. Appendix 1 includes a summary of the WSP report carried out on behalf of NIE Networks which provides more detail on the increase in demand attributed to an uptake in Low Carbon Technologies (LCTs). This information was used in NIE Networks' transmission demand forecast, and subsequently the derived demand forecast at Drumnakelly Main.

Transformers generally have a cyclic overload capability which varies according to the ambient temperature and the demand profile. At the Drumnakelly Main site the cyclic overload rating has been estimated at 95.4 MVA (106%) and 102.15 MVA (113.5%) in summer and winter respectively. This has been assessed based on the actual demand profile and typical transformer parameters. Further details on the cyclic overload ratings of the 110/33 kV transformers are presented in Appendix 2.

Based on the recorded demand for Drumnakelly Main, the peak demand on the winter peak day, whilst exceeding the 90 MVA nominal rating of the transformers, would be within the cyclic overload rating of the transformers up to about 2032. Loading beyond the cyclic rating of a transformer results in increased ageing over the long term. However, it is possible to load the transformer beyond the cyclic rating for a short time provided the winding temperature is monitored.

Beyond 2032 a post fault load transfer will be required to avoid thermally overloading the remaining in-service transformer, and to prevent overloading prior to the demand transfer the automatic disconnection of load may be required. This is allowed for in the TSSPS and DSSPS. It would be necessary to operate the 33 kV system radially during this time and if that radial operation was prolonged there could be a further risk to supplies.

Whilst an arrangement like this needs to be considered it is unlikely to ever be required because transformer faults are rare, and this would need to occur at peak demand in Winter. However, this is not sustainable long term as it provides no capacity for future load growth and the and by operating the 33 kV system radially there is an increased risk to supplies in the event of a secondary outage.

3.1.1 Summary

The underlying demand at Drumnakelly Main is in excess of the nominal rating of the 110/33 kV transformers. It remains below the estimated cyclic overload rating up to 2032. Beyond 2032, to maintain compliance and to manage the demand in fault conditions, a post fault demand transfer onto Waringstown Main will be required until the second transformer is restored. This may require the automatic disconnection of load, as allowed in the TSSPS and DSSPS, to prevent further overloads to the remaining in-service transformer. Further risks to supplies can occur due to the 33 kV system being operated radially. This arrangement is not sustainable longer term and provides no capacity for future load growth.

3.2 Armagh Distribution Network

The forecast load growth for each of the substations connected to this network indicates that the system peak demand will rise to approximately 50 MVA by 2029 and 55 MVA by 2033. Table 2 shows the measured maximum demand and forecast load for the Armagh area, with a detailed load per substation listed in Appendix 3.

Year	2021 (actual)	2025 (forecast)	2029 (forecast)	2033 (forecast)
Demand (MVA)	41.5	47.8	50.4	55.1

Table 2 - Armagh demand (historic and forecast)

The existing demand on the Armagh 33 kV network is in excess of its firm capacity, i.e. based on the capacity of three of the four circuits remaining operational. Whilst the system remains technically within the minimum security requirements for C2 class of supply of the Distribution System Security and Planning Standards (DSSPS)[1] the service level is well below what is normally provided. This is further described below:

- The firm capacity of this four circuit 33 kV network supplying Armagh City and surrounding area is 40 MVA (based on the most onerous 33 kV single circuit outage).
- The peak network load for 2021/22 was approximately 109% of the system's firm capacity.
- Over the 2021/22 winter, the system demand was in excess of the firm capacity for a total of 136 hours.

[1] Under N-1 two thirds of group demand restored within 15 minutes and Group demand within 3 hours.

- Based on NIE Networks' forecast the total demand on the network will increase to 132% of firm capacity by the end of RP7 (2031).
- The period at risk will increase from 136 hours to 1915 hours per annum by the end of RP7 (2031).

An outage on any one of the four circuits at peak load periods results in thermal overloading or low voltages on the remaining sections of network. Figure 3 below summarises these present and future issues.

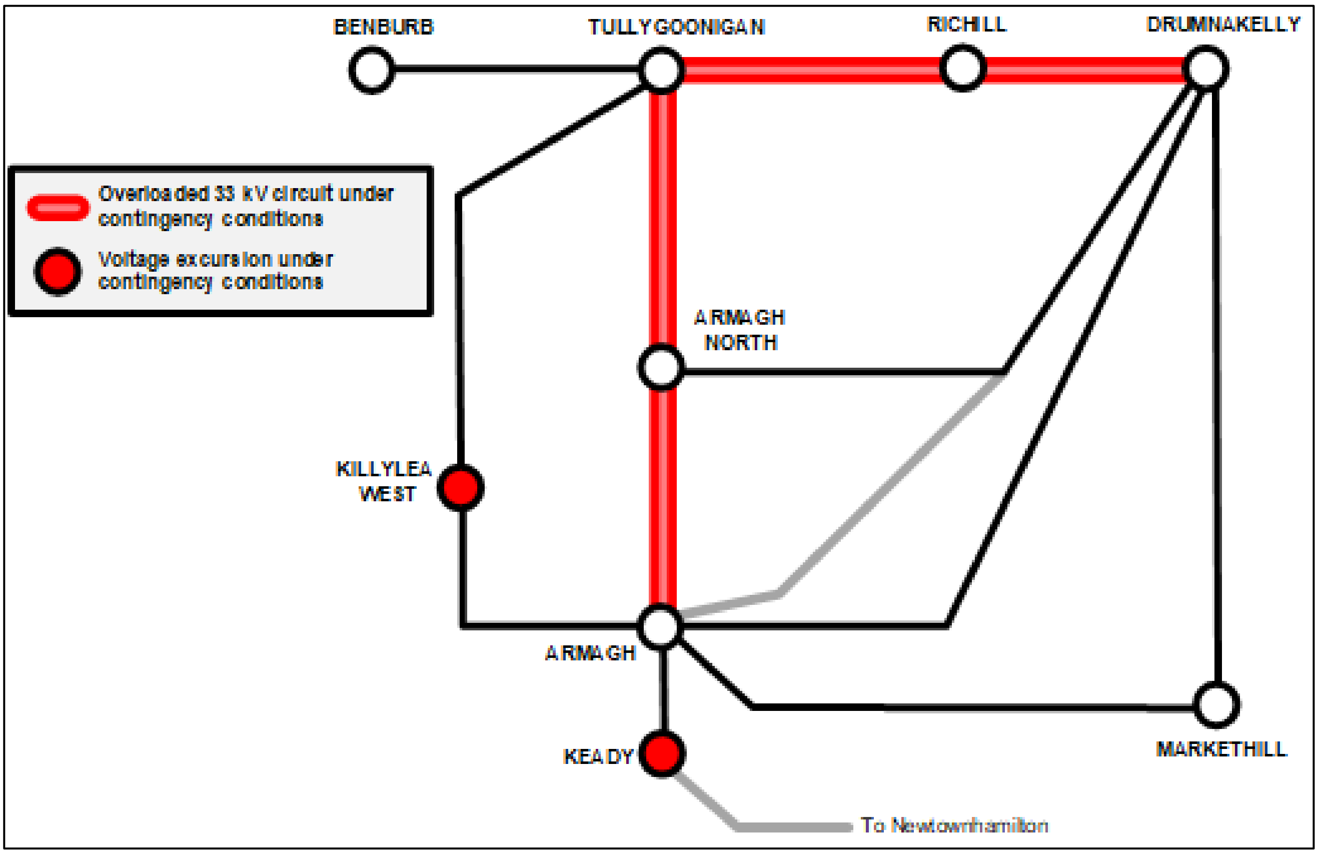

Figure 3 - Armagh Area 33 kV present and future network issues in contingency conditions

Figure 4 below shows the historic and forecast demand on the Armagh 33 kV network.

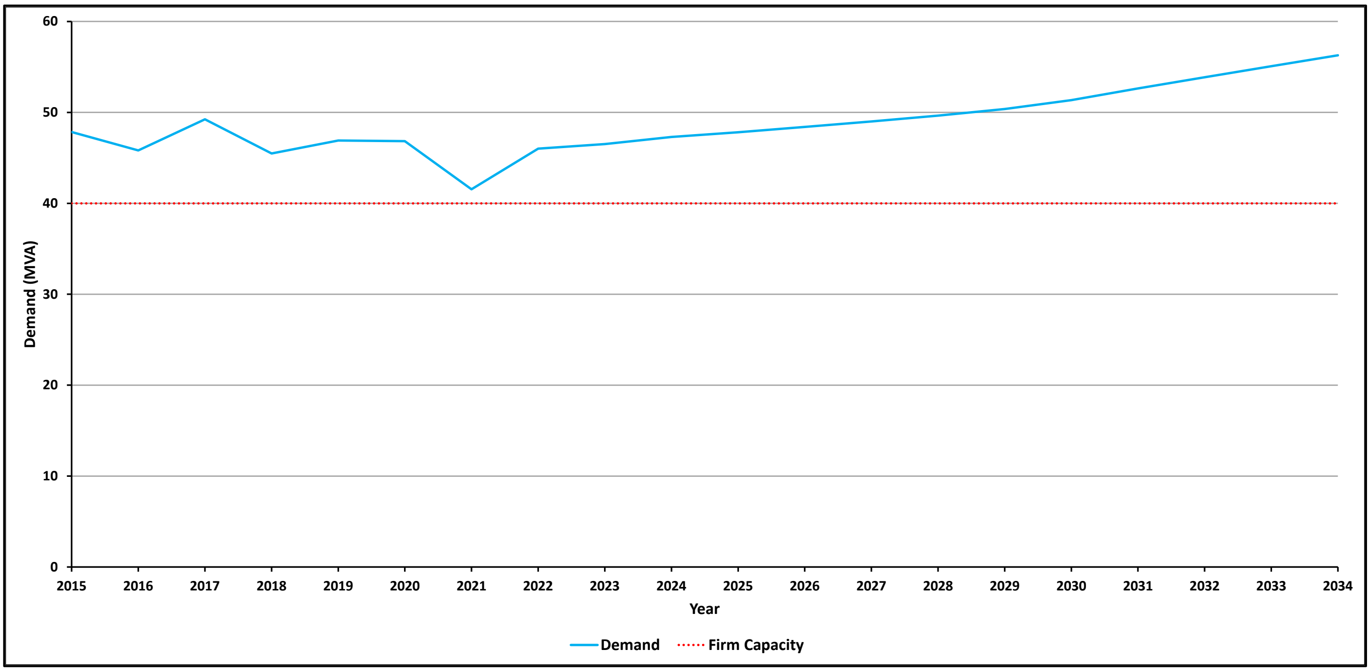

Figure 4 - Historic and forecast demand on the Armagh 33 kV network

Figure 4 shows that the maximum demand on the Armagh 33kV network has been in excess of the firm capacity for a number of years. It can be observed that in recent years the general trend in this area of the network has been decreasing demand. However, this is forecast to increase in the coming years due to the electrification of the heat and transport sectors. The decrease in demand has allowed for the current network risk described above to be managed through temporary network reconfigurations. This has enabled the distribution need to be considered in parallel with the transmission network limitations to evaluate the best long-term reinforcement solution for the Armagh network and to allow for coordinated, efficient and economic development of the transmission and distribution systems.).

3.2.1 Load Indices

Load Indices are a network output measure to show substation and network utilisation. The methodology for calculating the load index for a substation or network is to run an algorithm comparing the firm capacity with the actual demand. The output from the algorithm allows each substation or network considered to be placed in a Load Index (LI) banding category. The load Index banding is from LI1, which is defined as ‘having significant spare capacity’, up to LI5, which is defined as ‘fully utilised, mitigation required’.

Based on the information above, the Armagh 33 kV network is already classed as an LI5 in the Load Indices Regulatory Instructions and Guidance.

In the RP7 submission NIE Networks brought forward 32 discrete primary network reinforcement projects which require some form of intervention during the RP7 period (2025-2031) due to their classification as either an LI4 or LI5. Despite its classification as an LI5, NIE Networks did not include reinforcement for the Armagh 33 kV network as part of the RP7 submission due to the proposed D5 project for Armagh to address both transmission and distribution network limitations.

3.2.2 Value of Lost Load (VoLL) Analysis

NIE Networks has carried out a Value of Lost Load (VoLL) analysis to determine the impact on the four circuits supplying the Armagh area network. Using the load index data available from 2024-2035 and extrapolating the values out to 2050 (before flatlining from 2050 onwards) the total Megawatt hours (MWh) above the firm capacity (40 MVA) and the number of hours per year that the network could be at risk of overload was determined (the number of hours per year is presented as a percentage of the year). Additionally, using historic data from 1992-2024 of the recorded faults on the four 33 kV circuits, a fault probability percentage could be determined (which represents the likelihood of a fault on any of the four 33 kV circuits) – this value was calculated as 0.613%. Using the VoLL value for 2021/22 of £18.35k/MWh used by NIE Networks in their RP7 submission and applying inflation to uplift the price base to 2023/24 a final figure for VoLL is determined as £22.22k/MWh. This information can used to determine a financial cost for VoLL (for faults) by using the following equation [1]:

$$VoLL\ (Faults) = \begin{pmatrix} Total\ MWh \\ > 40\ MVA \\ firm \\ capacity \end{pmatrix} x \begin{pmatrix} No. of\ hrs \\ overloaded \\ (\% - percentage \\ of\ year \end{pmatrix} x \begin{matrix} Fault \\ probability \\ (\% - 0.613\%) \end{matrix} x \begin{pmatrix} VoLL\ Value \\ £/MWh \\ - £22.22k \\ /MWh \end{pmatrix} \quad [1]$$

Historic data from 1992-2024 of the recorded planned outages (and their duration) was used to determine the impact on future planned maintenance outages. Normally planned outages are programmed at a time in which the impact to the rest of the distribution system is minimal and the load can remain stable (without the risk of losing customers) on the remaining in-service network. It is assumed that any planned maintenance can be scheduled during off-peak times until 2035, after which it is assumed that any maintenance will unavoidably result in a loss of load. This has also been calculated as a probability, with a value of 0.438%. Using this information a financial cost for VoLL (for maintenance) can be determined by the following equation [2]:

$$VoLL\ (Maintenance) = \begin{pmatrix} Total\ MWh \\ > 40\ MVA \\ firm \\ capacity \end{pmatrix} x \begin{pmatrix} No.of\ hrs \\ overloaded \\ \% - \\ percentage \\ of\ year \end{pmatrix} x \begin{matrix} OHL \\ Maintenance \\ (\% - 0.438\%) \end{matrix} x \begin{pmatrix} VoLL\ Value \\ £/MWh \\ - £22.22k \\ /MWh \end{pmatrix} \quad [2]$$

Finally using the load index data from 2024-2035 it was possible to determine the total Megawatt hours (MWh) when the four 33 kV circuits were above the normal system operation (NSO) limit of 52.5 MVA i.e. during normal operating conditions and still with a potential risk of overload on the four in-service 33 kV circuits. Using this information a financial cost for VoLL (NSO) can be determined by the following equation [3]:

$$VoLL\ (NSO) = \begin{pmatrix} Total\ MWh \\ > 52.5\ MVA \\ NSO\ Limit \end{pmatrix} x \begin{pmatrix} VoLL\ Value \\ £/MWh - \\ £22.22k/\ MWh \end{pmatrix} \quad [3]$$

Using these calculations the following costs from the VoLL analysis are obtained:

- VoLL (Faults) = £45.34m;
- VoLL (Maintenance) = £32.00m;
- VoLL (NSO) = £181.58m; and
- Overall total cost of VoLL (from 2024-2064) = £258.93m

For further information on this analysis, see Appendix 4.

3.2.3 Summary

The Armagh area distribution network is fed from Drumnakelly 110/33 kV substation and has been identified as an LI5. NIE Networks determined the demand was in excess of the network capacity for 136 hours of the 2021/22 winter period, with this risk set to rise over the coming years due to load growth in the area. Sections of the distribution network are at risk of overloading and, without short-term operational measures, voltage levels would be below statutory limits at some substations. Reinforcement into the area is required to resolve these thermal and voltage constraints.

VoLL analysis has been used to financially assess the impact of future potential faults, planned maintenance outages and normal system operation (NSO) on the 33 kV network supplying the Armagh area. This analysis uses load index data (and extrapolating out to 2050), historic outage information to determine a fault probability and maintenance probability (from 1992-2024 on the four 33 KV circuits supplying the Armagh area) and a VoLL figure of £22.22k/MWh (which is then updated based on the Harmonised Index of Consumer Prices (HICP)). The overall total cost of VoLL from faults, maintenance and during normal system operation from 2024-2064 is estimated to be £258.93m.

3.3 Potential Future Needs – Demand at Newry

Newry Main 110/33 kV substation is supplied via a 43 km 110 kV double circuit tower line from Tandragee, constructed in 1965. The substation includes two 90 MVA 110/33 kV transformers and a 2,000A 33 kV mesh. Newry Main supplies Newry city and the surrounding area. The 33 kV distribution system supplied from Newry Main is poorly interconnected with the neighbouring bulk supply points of Drumnakelly Main and Ballynahinch Main due in part to the geographical constraints imposed by the Mourne Mountains.

The 110 kV double circuit tower line that supplies Newry Main has a firm capacity of 82 MVA, 95 MVA and 103 MVA in summer, autumn and winter respectively. NIE Networks' forecast transmission demand shows the peak demand in 2027 to be 83 MVA; therefore a restring of the 110 kV circuits is not deemed necessary. SONI has included a project in the Transmission Development Plan, Northern Ireland (TDPNI) 2023 to reinforce the network at Newry.

As mentioned above the 33 kV network from Newry Main has very limited re-supply in the event of a maintenance-trip outage of the two 110 kV circuits. The TSSPS does not provide a requirement to cover a second circuit outage for the level of demand at Newry. It does, however, require that demand can be restored within the timescales required to restore the planned outage. The DSSPS is of similar standard but includes a caveat for a double circuit outage which states:

"A loss of supply not exceeding 60 secs is considered as an immediate restoration. The Recommendation is based on the assumption that the time for restoration of Full group demand after a second circuit outage will be minimised by the scheduling and control of planned outages, and that consideration will be given to the use of rota load shedding to reduce the effect of prolonged outages on consumers. It is normal to aim for restoration of supply to 1/3 Group Demand within 3 hours after a second circuit outage to prevent widespread and prolonged supply interruption."

The double circuit tower line that supplies Newry will require replacement of the earth wire within the next 15 to 20 years. Currently, for safety reasons, the replacement of an earth wire on a double circuit tower line requires a double circuit outage. It is possible that alternative work methods might be approved in the future. At present, however, the only approved method to ensure supplies are maintained and a double circuit outage is facilitated would be to construct a temporary single circuit diversion section by section. This would be an extremely costly method to facilitate this work.

Transmission reinforcement into the Armagh area would improve the resupply into Newry Main distribution system via the Keady to Newtownhamilton 33 kV overhead line in the event of a 110 kV double circuit outage. Transmission reinforcement into Armagh would also provide infrastructure that can be developed further to enhance the resupply capacity into the Newry Main distribution system to a much greater degree than is currently available. This would help, in part, to address the issues identified above and to help with any reinforcement works that will take place in the future Newry Upgrade project.

4 Conclusion

In conclusion, NIE Networks has identified that at times of high electrical demand in the Armagh area, the firm capacity of the 33 kV distribution network is exceeded. The distribution network supporting the demand in this area of Armagh is supplied from Drumnakelly. Demand at Drumnakelly presently exceeds the nominal rating of the 110/33 kV transformers. It has been determined that the site remains within the cyclic overload rating of the transformers up to 2032.

Beyond 2032 to maintain compliance and manage demand in fault conditions a post fault demand transfer onto Waringstown Main will be required until the second transformer is restored. This would result in the 33 kV system operating radially at this time, and if that radial operation was prolonged there could be further risk to supplies. To prevent overload prior to the demand transfer taking place the automatic disconnection of load may be required, which is allowed for in the TSSPS and DSSPS. Whilst an arrangement like this needs to be considered it is unlikely to ever be required because transformer faults are rare, and this would need to occur at peak demand in Winter. However, this is not sustainable long term as it provides no capacity for future load growth and by operating the 33 kV system radially there is an increased risk to supplies in the event of a secondary outage.

The most pressing need is resolving the potential overloading of the 33 kV distribution network supplying the Armagh area. Sections of this network are at risk of overloading and voltage levels would be below statutory limits at some substations. Reinforcement into the area is required to resolve these thermal and voltage constraints. There is also a need to provide additional transmission capacity at Drumnakelly; however, slow demand growth means this need does not need to be addressed immediately. The urgency of the transmission need will be determined by two factors:

- The cyclical overload capability of the Drumnakelly 110/33 kV transformers; and
- Uptake of Low Carbon Technologies through the decarbonisation of heat and transport (and therefore increased electrical demand) in line with the Paris Agreement and the UK's 2050 Net Zero targets.

Value of Lost Load (VoLL) analysis has been completed using load index data of the Armagh Area 33 kV system, historic data on outages and maintenance duration for the four 33 kV circuits and other assumptions. This has determined that without reinforcement the overall total cost of VoLL from faults, maintenance and during normal system operation from 2024-2064 is estimated to be £258.93m.

5 Appendices

Appendix 1 - Forecasting of low carbon technology deployment in Northern Ireland – Summary from WSP report – March 2023

Low Carbon Technology Uptake

In December 2021 the Northern Ireland government published their new Energy Strategy Paper, The Path to Net Zero Energy, which sets out the overall strategy and energy targets to align Northern Ireland (NI) with overall International and UK carbon reduction targets that are required as part of the collective global contribution to prevent runaway climate change. A target was set for 70% of total electricity consumption to be met from a diverse mix of renewable energy sources (RES) by 2030. This target has subsequently been increased by NI Government, through the Climate Change Act (Northern Ireland), 2022, to 80% of electricity consumption to be met from RES by 2030.

Alongside this RES target is a target to reduce average building energy consumption by 25% by 2030, this equates to an average reduction in the region of 3% per year on 2021 consumptions. WSP consider this to be an ambitious target when compared to existing LCT forecasts undertaken by other organisations and it is probable that a notable proportion of this target will need to be achieved via the roll out of heat pumps, which inherently produce building energy reductions due to their effective energy conversion efficiencies being 3 to 4 times greater than for conventional boilers.

Demand Forecasts

The main increases in projected electricity demand are as a result of decarbonising, primarily from the electrification of, heat and transport. The uptake of EVs and the associated charging infrastructure produces large additional demands on the electricity networks. Similarly, the electrification of heat also produces large additional demands. EV demands are relatively uniform across the year, but do rise in winter due to the need for greater usage of vehicle lights and heating. The heat pump demand is much more pronounced in the cold winter weather.

A range of existing studies have been used to inform this NI LCT forecast update, and where relevant studies or data was not available specifically for NI then data has been translated to NI from existing GB forecasts, for example National Grid's GB Future Energy Scenario (FES) forecasts.

It is of note that the production of hydrogen has not been accounted for in the overall demand, and the decarbonising of ports, shipping, aviation and railways have not been accounted for. If these are dominated by electrification or NI produced Green Hydrogen (rather than for example imported low/zero carbon fuels), then this will impose an upward movement on the demand and associated RES generation forecasts.

Heat Pump and EV Charger Volumes - Central Scenario 2030

- Heat Pumps - 120,000
- EV's - 300,000

The central demand forecasts indicate a projected increase of around 20% in electricity demand by 2030, and in the region of 130-140% increase by 2050 (dependent on the uptake of different technology and energy strategies to achieve net zero).

The study has considered some of the recent rapid rises in fossil fuel costs, however the long-term impact of current international events is not currently known and cannot be fully accounted for. Where the current elevated costs for fossil fuels were to be maintained, then the business case for RES generation, EVs and Heat Pumps all improve. In which case an accelerated uptake of LCTs may occur which would bring forward some of the projected uptake rates set out under the central scenario in this report, and increase the likelihood of greater alignment with the high uptake demand and generation scenarios. The final 2050 capacities and demands, which should be considered for longer term network planning, should not be significantly affected as these all consider an almost entirely fossil fuel free electricity system.

Appendix 2 – Cyclic overload ratings of transformers

This appendix aims to estimate the cyclic overload ratings of the oil-filled power transformers installed in Drumnakelly Main.

The methodology applied is based on IEC 60076-7:2005, Ed.1.0, Power Transformers – Part 7 Loading guide for oil-immersed power transformers.

The principles used in this methodology are the following:

- The transformers should operate on a normal cyclic loading[2];
- Cycles take 24h (or 1440min), as per the evolution of demand in the substation;
- No loss-of-life during each cycle beyond unity ageing;
- The transformers will have sufficient time to enter in thermal steady state, before a change of the load factor (K) occurs.
- The demand profile curve will be approximated to a theoretical curve with two steps that will represent the periods of the cycle with lower and higher demand.

The final objective is to ensure that the cyclic overload ratings does not increase ageing of the transformers, but at the same time exploit the feature of balancing ageing between periods of time lower and higher load, so that in the end of a cycle there is no excessive deterioration of its paper windings insulation.

This means that the loss-of-life of the transformer in the end of a cycle should be equal to the duration of the cycle.

Demand profile

For this report, the year 2023 was studied and the data for transformer load was extracted from NIE Networks PI Historian (and is shown in MVA).

[2] Normal cyclic loading is defined in IEC 60067-7, page 8, as operational contexts where "higher ambient temperature or a higher-than-rated load current is applied during part of the cycle, but, from the point of view of relative thermal ageing rate (according to the mathematical model), this loading is equivalent to the rated load at normal ambient temperature. This is achieved by taking advantage of low ambient temperatures or low load currents during the rest of the load cycle".

An assumption made for this report is that to simulate a N-1 situation, the transformer load is the sum of the two individual transformers on any given day, shown in Equation [1].

$$Tx_1 + Tx_2 = Tx_{n-1} \quad [1]$$

As the load profile can fluctuate day-to-day, the best way to get a representative load profile was to average across the month. Figure 2-1 below shows monthly average load profile. As expected, the colder months tend to have a higher load profile.

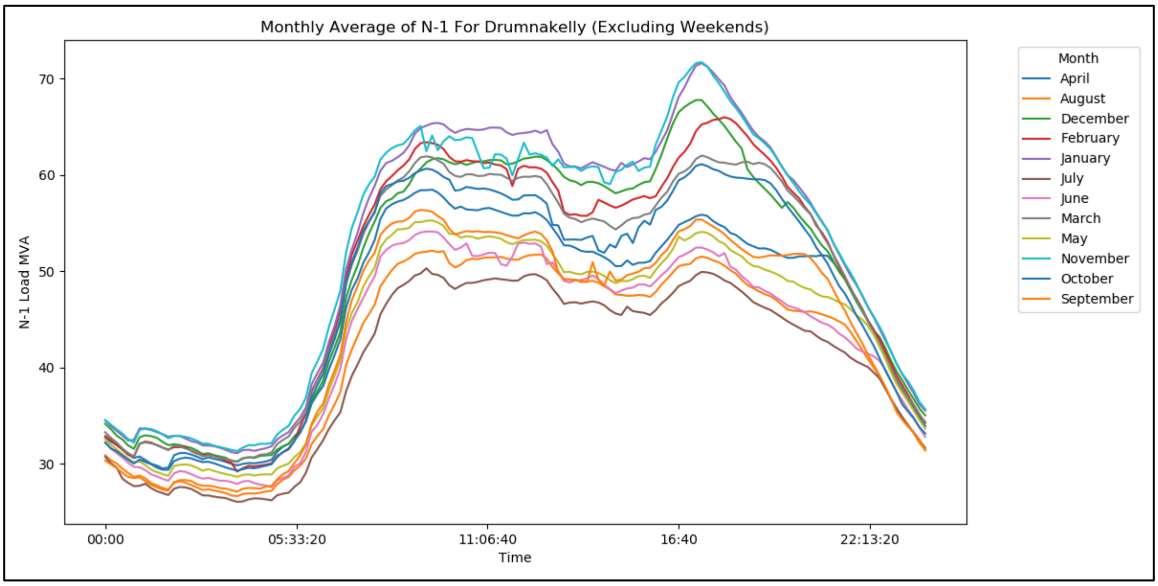

Figure 2-1 - Drumnakelly Transformer 1 Monthly Load Profile

This can be further averaged across the months to give a seasonal load profile, shown in Figure 2-2 below.

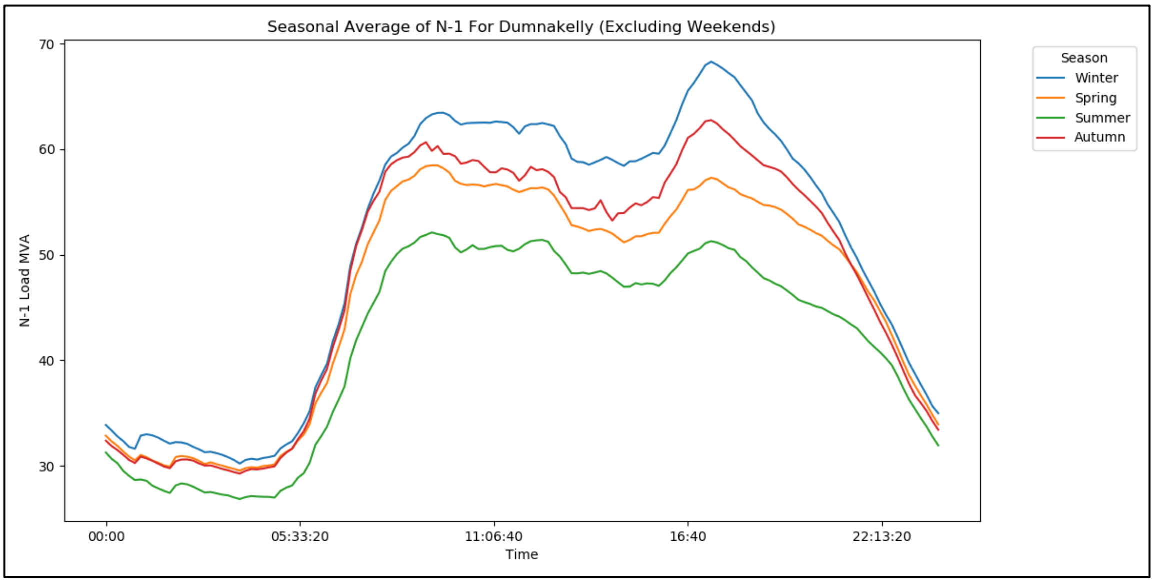

Figure 2-2 – Drumnakelly seasonal load profile

The typical demand profiles Drumnakelly Main on a working day with maximum demand on the Summer Peak Period and the Winter Peak Period are presented, respectively, in Figure 2-3 and Figure 2-4.

It can be observed that the measured demand has a cyclic behaviour of 24h that translates the mixed residential and commercial background of the demand in Drumnakelly Main, with an evening peak, typically between 17:00 and 19:00, which is more evident during the Winter Peak Period.

To carry out the cyclical overload calculations a step function is mapped onto the curves. This step function gives the high and the low levels for the daily cycle. For Summer and Winter these are shown in Figures 2-3 and 2-4 below.

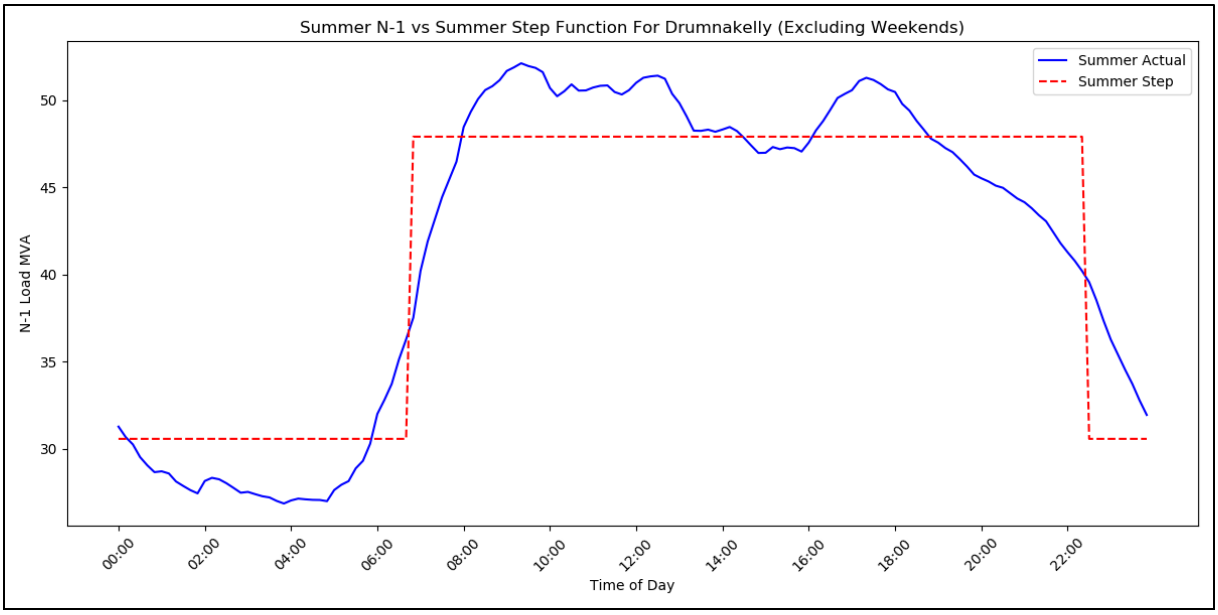

Figure 2-3 – Typical demand profiles on a working day (Maximum demand Summer Peak Period) - Drumnakelly N-1 Summer step functions

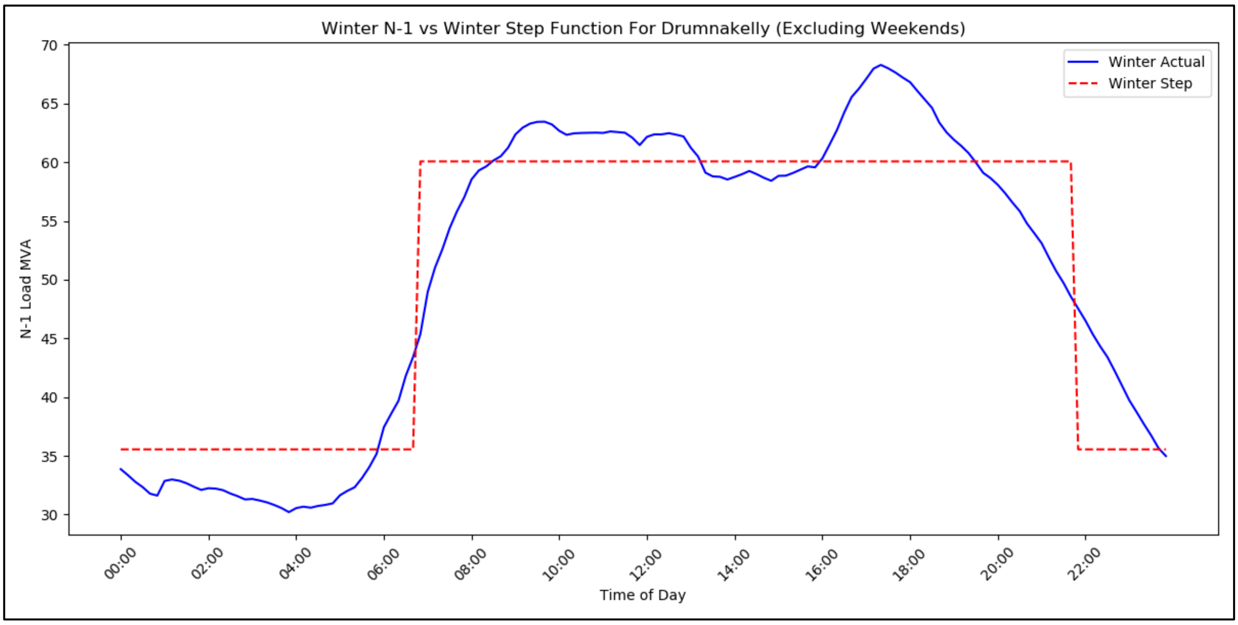

Figure 2-4 – Typical demand profiles on a working day (Maximum demand Winter Peak Period) - Drumnakelly N-1 Winter step functions

Figure 2-3 and Figure 2-4 indicate that from the theoretical measured demand there is a lower step and a higher step, which were determined based on the average measured demand during the Summer and Winter periods.

The step functions were defined in order to maximise the correlation coefficients (R) and the coefficient of determination (R^2). These are two values that verify how close the step functions match with the original demand curve. For R values, anything over 0.9 is considered very good, and R^2 anything over 0.8 is the target.

The values T_1 and T_2 represent the number of minutes at low load and high load respectively.

The values K_1 and K_2 represent the load at low load and high load respectively. These are initially worked out as an absolute value, in MVA, and then they are calculated as per unit (PU) based on the transformer nominal rating (90 MVA). These values are presented in Table 2-1 below.

Period	R	R^2	T_1 / T_2	K_1 / K_2 (MVA)	K_1 / K_2 (PU)
Summer Peak	0.928	0.874	530 / 910	30.56 / 47.90	0.339 / 0.43
Winter Peak	0.922	0.879	570 / 885	35.55 / 60.07	0.395 / 0.577

Table 2-1 – Statistical Analysis of Step Functions

The limitation on the cyclic overload factor for a transformer depends on several factors. If we exclude the endogenous characteristics of the transformer, this factor is very influenced by ambient temperature, the values of the load factor during the period of load below the nominal rating and the time relation between lower and higher periods of load.

These are the reasons why it is important to determine the transformer's behaviour during Summer and Winter Peak Periods which are the periods where the extremes of these factors occur.

Relative ageing rate and transformer Insulation loss-of-life

Temperature distribution in the transformers' windings is not uniform, and the part that is operating at the highest temperature will normally undergo the greatest deterioration.

The location on the windings with the highest temperature is defined as the hot-spot, and the rate of ageing in the hot-spot[3] is defined by the relative ageing rate (V) as per Equation [2].

For the purpose of this assessment, it was considered that the non-thermally upgraded insulation paper was used in the windings insulation and transformer construction. This means that unity relative ageing rate corresponds to 98°C.

$$V = 2^{\frac{\theta_h - 98}{6}} \quad [2]$$

Where;
θ_h is the hot spot temperature in °C

The loss of life of a transformer over a period of time is defined by equation [3]

$$\int_{t_1}^{t_2} V dt \quad [min] \quad [3]$$

Where;
t_2: is the time spent at high load
t_1: is the time spent at low load

[3] The hotspot is considered the hottest spot of the windings

Hot Spot and top-oil temperatures

Using the methodology based on 'IEC 60076-7:2005, Ed.1.0, Power Transformers – Part 7 Loading guide for oil-immersed power transformers' there are two ways to describe the hot-spot and the top-oil[4] temperatures as functions of time.

The approach taken will be based on the exponential equations' solutions described in Section 8.2.2 of this standard, which are solutions of the differential equations that model the thermal behaviour of the transformer[5].

This approach is suitable for cases where increasing load steps are followed by decreasing load steps or vice versa, which is valid for the theoretical demand curve in Drumnakelly Main.

Due to the time length of each step the hot-spot-to-top-oil gradient ($\Delta\theta h$) will obtain steady state.

The solution of the differential equations for the hot-spot temperature are explained by Equations [4] and [5], that model the temperature behaviour for the lower and higher steps[6] of the load factor[7], respectively:

$$\theta_h(t) = \theta_a + \Delta\theta_{or} \cdot \left(\frac{1+R\cdot K^2}{1+R}\right)^x + \left[\Delta\theta_{oi} - \Delta\theta_{or} \cdot \left(\frac{1+R\cdot K^2}{1+R}\right)^x\right] \cdot f_3(t) + Hg_r \cdot K^y \quad [4]$$

$$\theta_h(t) = \theta_a + \Delta\theta_{oi} + \left[\Delta\theta_{or} \cdot \left(\frac{1+R\cdot K^2}{1+R}\right)^x - \Delta\theta_{oi}\right] \cdot f_1(t) + \Delta\theta_{hi} + (Hg_r \cdot K^y - \Delta\theta_{hi}) \cdot f_2(t) \quad [5]$$

---

[4] The top-oil temperature is the temperature of the oil at the top of the tank.

[5] The differential equations of the top-oil and hot-spot temperatures are presented on section C.3 of the Standard

[6] Lower steps correspond to periods of a load factor smaller or equal to the unit. Higher steps correspond to periods of a load factor higher or equal to the unit.

[7] Load factor is defined as the load current / rated current.

Where;

θa is the ambient temperature, in °C.

$\Delta\theta or$ is the top-oil (in tank) temperature rise ($\Delta\theta o$) in steady state, at rated losses (no-load losses + load losses), in K (or °C).

R is the ratio of load losses at rated current to no-load losses, dimensionless.

K is the load factor, dimensionless.

x is the exponential power of total losses versus top-oil (in tank) temperature rise (oil exponent), dimensionless.

$\Delta\theta oi$ is the top-oil (in tank) temperature rise at the start (of a step), in kelvin, K (or °C).

H is the hot-spot factor, dimensionless.

gr is the average-winding-to-average-oil (in tank) temperature gradient at rated current, in K (or °C).

y is the exponential power of current versus winding temperature rise (winding exponent), dimensionless.

$\Delta\theta hi$ is the hot-spot-to-top-oil (in tank) gradient at start (of a higher step), in K (or °C).

The auxiliary functions $f_1\,(t)$, $f_2\,(t)$ and $f_3\,(t)$ are defined by Equations [6], [7] and [8].

$$f_1(t) = 1 - e^{\frac{-t}{\tau_0/k_{22}}} \quad [6]$$

$$f_2(t) = k_{21}\left(1 - e^{\frac{-t}{k_{22}\tau_w}}\right) - (k_{21} - 1)\left(1 - e^{\frac{-t}{\frac{\tau_0}{k_{22}}}}\right) \quad [7]$$

$$f_3(t) = e^{\frac{-t}{k_{11}\tau_0}} \quad [8]$$

Where ;

k_{11}, k_{21} and k_{22} are thermal model constants, dimensionless.

τ_o is the average oil time constant, in min.

τ_w is the winding time constant, in min.

By solving the differential equation for top-oil temperature, on IEC 60076-7:2005, Section C.3, Equation C.1, for the cases of a lower step and a higher step for the load factor, the solutions attained are presented in Equations [9] and [10] respectively.

$$\theta_o(t) = \theta_a + \Delta\theta_{or} \cdot \left(\frac{1+R\cdot K^2}{1+R}\right)^x + \left[\Delta\theta_{oi} - \Delta\theta_{or} \cdot \left(\frac{1+R\cdot K^2}{1+R}\right)^x\right] \cdot f_3(t) \qquad [°\mathrm{C}] \qquad [9]$$

$$\theta_o(t) = \theta_a + \Delta\theta_{oi} + \left[\Delta\theta_{or} \cdot \left(\frac{1+R\cdot K^2}{1+R}\right)^x - \Delta\theta_{oi}\right] \cdot f_1(t) \qquad [°\mathrm{C}] \qquad [10]$$

Equations [4] to [10] were defined from the IEC standard to model the thermal behaviour in the transformer as independent functions, with specific initial conditions, and not as piecewise functions.

To follow the same principle, the equations will be treated as independent in this document.

The top-oil temperature rise in the transformer tank and the hot-spot-to-top-oil (in tank) gradient, at a certain load are defined by Equations [11] and [12].

$$\Delta\theta_o = \theta_o - \theta_a \qquad [\mathrm{K\ or\ °C}] \qquad [11]$$

$$\Delta\theta_h = \theta_o - \theta_a \qquad [\mathrm{K\ or\ °C}] \qquad [12]$$

Parameters of the hot-spot and top-oil temperature functions

For medium size power transformers with Oil Natural, Air Forced (ONAF) cooling, the recommended thermal characteristics for the exponential equations are presented in Table 2-2.

Parameters			Notes
Oil exponent	x	0.8	For IEC 60076-7:2005 (page 6) with ON cooling
Winding exponent	Y	1.3	For IEC 60076-7:2005 (page 6) with ON or OF cooling
Loss ratio	R	17.2	R = Load Losses at rated current / No Load losses. This is obtained from the NIEN TSS
Average winding to average oil temperature in k (or ˚C)	g_r	22.76	Extrapolated from data in IEC 60076-7:2005 Sections 8.1.3, for 120 kV and 410 kV windings
Hot-spot factor	H	1.3	Adopted from example in IEC 60076-7:2005 Table E.1
Oil time constant, in min	τ_o	150	IEC 60076-7:2005 Table 5
Winding time constant, in min	τ_w	7	IEC 60076-7:2005 Table 5
Thermal model constant	k_{11}	0.5	IEC 60076-7:2005 Table 5
Thermal model constant	k_{21}	2.0	IEC 60076-7:2005 Table 5
Thermal model constant	k_{22}	2.0	IEC 60076-7:2005 Table 5
Top-oil (in tank) temperature rise, in K (or ˚C)	$\Delta\theta_r$	52	Adopted from example in IEC 60076-7:2005, Table E.1

Table 2-2 - Characteristics related to the loading ability of the transformer

All of these parameters are constants, apart from Loss Ratio, R, which is the Load losses/No load Losses obtained from NIE Networks' Transmission Services Specification (TSS).

The top-oil temperature rise in the tank above ambient temperature at rated losses ($\Delta\theta or$) can be calculated with the help of Equations [10] and [11], and the hot-spot temperature rise above top-oil temperature in the tank at rated current ($\Delta\theta \mathrm{h}r$), which can be determined either by direct measurement during a heat-run test or by a calculation method validated by direct measurements. IEC 60076-7:2005, Sections 8.1.2 and 8.1.3 describe the procedures to determine $\Delta\theta hr$. Since there isn't information about this parameter, the value presented is adopted from the example in IEC 60076-7:2005, Table E.1.

The same procedure was adopted for the hot-spot factor, which is winding-specific and should be determined on a case-by-case basis. See IEC 60076-7:2005, Sections 8.1.3 and 8.1.4.

Ambient Temperature

The ambient temperature is a parameter of the $\theta h\ (t)$ equations, but because it is not dependent of the physical characteristics of a transformer, it is treated differently.

Air temperature has a significant impact on the capacity of a transformer to dissipate heat.

IEC 60076-7 Page 32 states: For design and test considerations, the following equivalent temperatures are taken as ambient temperature.

a) The yearly weighted ambient temperature is used for thermal ageing calculation.

b) The monthly average temperature of the hottest month is used for the maximum hot-spot temperature calculation.

To avoid overloading the transformer by oversizing the cyclic overload factors, the monthly average temperature of the hottest month will be considered to represent the Summer and Winter Peak Periods. This information was obtained from the Met Office National Climate Information Centre database[8].

[8] https://www.metoffice.gov.uk/research/climate/maps-and-data/uk-and-regional-series

For 2024, the values of the air temperature to be considered on this assessment are the following:

Summer Peak Period: θa = 14.4 ℃.

Winter Peak Period: θa = 5.69 ℃.

Limits on normal cycling loading

The current and temperature limits applicable to normal cycling loading[9] in medium power transformer are presented in table 2-3.

Limits	
Current (or load factor, K) (PU)	1.5
Wind hot-spot temperature, θ_h, and metallic parts in contact with cellulosic insulation material (°C)	120
Top-oil temperature, θ_o (°C)	105

Table 2-3 – Limits applicable to normal cyclic loading

Initial Conditions

Figure 2-5 presents a typical theoretical demand profile split in lower and higher steps.

It will be considered that each cycle will start on the descending flank. When there is a change of level the time will restart for the purpose of this analysis.

[9] All current and temperature limits applicable to loading beyond nameplate ratings are presented in Table 4 of the Standard

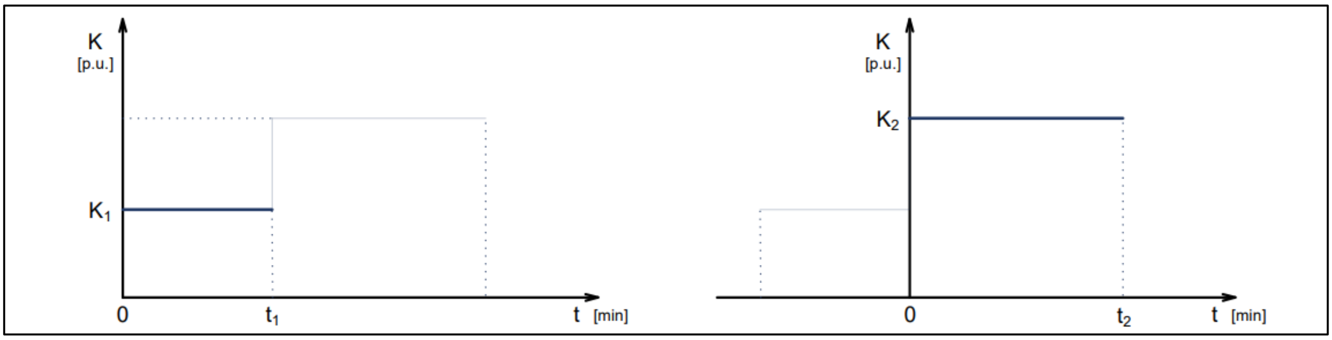

Figure 2-5 – Typical theoretical demand profile split in lower and higher steps

A cycle takes 1 day, which is 1440 minutes.

Each load factor step will take sufficient time so that the temperature change with time will be negligible. This means that the thermal behaviour of the transformer will be in steady state. So, when a change of load factor occurs, the initial conditions are the following:

- For the lower step $(0 \leq t \leq t_1)$ there is a transient before and after it, but due to the difference in time between the transient and the steady state the system is considered to be in steady state, so the following equations describe the behaviour of it. $\theta_h(t)$ and $\theta_o(t)$ need to be calculated (using equations [3], [7] and [8]).

$$\theta_h(t) = \theta_a + \Delta\theta_{or} \cdot \left(\frac{1 + R \cdot K^2}{1 + R}\right)^x + \left[\Delta\theta_{oi} - \Delta\theta_{or} \cdot \left(\frac{1 + R \cdot K^2}{1 + R}\right)^x\right] \cdot f_3(t) + Hg_r \cdot K^y$$

$$\theta_o(t) = \theta_a + \Delta\theta_{or} \cdot \left(\frac{1 + R \cdot K^2}{1 + R}\right)^x + \left[\Delta\theta_{oi} - \Delta\theta_{or} \cdot \left(\frac{1 + R \cdot K^2}{1 + R}\right)^x\right] \cdot f_3(t)$$

The initial condition, ie $\Delta\theta_{oi}(0)$ need to be calculated, it can be written as;

$$\Delta\theta_{oi} = \theta_{oi} - \theta_a$$

The thermal system is assumed to be in steady state, so;

$$\frac{d\theta_o(t)}{dt} = 0$$

Then;

$$\Delta\theta_{oi}(t_0^-) \cong \Delta\theta_{or}\left(\frac{1 + RK_2^2}{1 + R}\right)^y$$

As $f(0^-) \to 1$

Therefore, our overall equation is;

$$\theta_{h1}(t) = \cdots$$

$$\left[\theta_a + \Delta\theta_{or} \cdot \left(\frac{1+R\cdot K_1^2}{1+R}\right)^x + Hg_r \cdot K^y\right] + \left[\Delta\theta_{or}\left(\frac{1+R\cdot K_2^2}{1+R}\right)^x - \Delta\theta_{or} \cdot \left(\frac{1+R\cdot K_1^2}{1+R}\right)^x\right] \cdot e^{\frac{-t}{\tau_0\, k_{11}}}$$

[12]

The two parts are bracketed together because everything in the left bracket is known and will simplify down to a constant.

- For the higher step $(t_1 \leq t \leq t_2)$ since the graph is split into two, the time bounds are $(0 \leq t \leq t_2)$. The equations used are [4], [5] and [6].

So both $\Delta\theta_{oi}(0)$ and $\Delta\theta_{hi}(0)$ will have to be calculated.

Using initial conditions of;

$t = t_1^-$and $K = K_1$

$$\theta_o(0^-) = \theta_a + \Delta\theta_{or}\left(\frac{1 + R \cdot K_1^2}{1 + R}\right)^x + \left[\Delta\theta_{oi} - \Delta\theta_{or} \cdot \left(\frac{1 + R \cdot K_1^2}{1 + R}\right)^x\right] \cdot f_3(0^-)$$

It is assumed that $f_3(t_-^1) \to 0$ therefore;

$$\Delta\theta_{oi}(0^-) \cong \Delta\theta_{or}\left(\frac{1 + R \cdot K_1^2}{1 + R}\right)^x$$

And;

$$\Delta\theta_{hi}(0^-) = Hg_r K_1^y$$

This makes the overall equation;

$$\theta_{h2} = \left[\theta_a + \Delta\theta_{or} \cdot \left(\frac{1+R\cdot K_1^2}{1+R}\right)^x + Hg_r \cdot K^y\right] + \left[\Delta\theta_{or}\left(\frac{1+R\cdot K_2^2}{1+R}\right)^x - \Delta\theta_{or} \cdot \left(\frac{1+R\cdot K_1^2}{1+R}\right)^x\right] \cdot \left(1 - e^{\frac{-t}{\tau_0\, k_{11}}}\right) + \left(Hg_r K_2^y - Hg_r K_1^y\right)\left[k_{21}\left(1 - e^{\frac{-t}{k_{22}\tau_w}}\right) - (k_{21} - 1)\left(1 - e^{\frac{-1}{\left(\frac{\tau_0}{k_{22}}\right)}}\right)\right]$$

Calculation of cyclic overload factors

The cyclic overload factors are influenced by several variables and for the purpose of this document, the only dependent variable to calculate is the higher step, K_2.

To ensure that the ageing of the transformer is not accelerated, but at the same time utilising the overload capacity during periods of cyclic normal loading, the loss-of-life is expressed in [14] for a daily cycle:

$$L(t, K_2) = L_1(t, K_2) + L_2(t, K_2) = \int_0^{t_1} V_1\big(\theta_{h1}(t, K_2)\big)dt + \int_0^{t_2} V_2\big(\theta_{h2}(t, K_2)\big)dt = 1440 \qquad [14]$$

Factors will be calculated for the Summer and Winter Peak Periods.

The parameters and the independent variables, K_1 and θa, will assume the values identified above for each Peak Period.

Subbing [12] and [13] into [14] gives us an expression to calculate K_2 given all of the initial conditions and assumptions we have made, these can go into a python code that is as follows:

Calculated constants

```
alpha_k1 = d_theta_or * ((1 + R * K1**2) / (1 + R))**x

a = theta_a + H * g_r * (K1**y) + alpha_k1

# Define the integrand functions

def integrand_h1(t, K2):

    theta_h1 = a + (d_theta_or * ((1 + R * K2**2) / (1 + R))**x - alpha_k1) * np.exp(-t / (k_11
* tau_o))

    return 2**((theta_h1 - 98) / 6)

def integrand_h2(t, K2):

    term1 = a + (d_theta_or * ((1 + R * K2**2) / (1 + R))**x - alpha_k1) * (1 - np.exp(-t / (k_11
* tau_o)))

    term2 = (H * g_r * K2**y - H * g_r * K1**y) * (k_21 * (1 - np.exp(-t / (k_22 * tau_w))) -
(k_21 - 1) * (1 - np.exp(-t / (tau_o / k_22))))

    theta_h2 = term1 + term2

    return 2**((theta_h2 - 98) / 6)

# Define the function to solve

def equation(K2):

    integral_h1, _ = quad(integrand_h1, 0, t1, args=(K2))

    integral_h2, _ = quad(integrand_h2, 0, t2, args=(K2))

    return integral_h1 + integral_h2 - 1440

# Solve for K2

K2_initial_guess = 1.0

K2_solution = fsolve(equation, K2_initial_guess)
```

```
print(f"The value of K2 is: {K2_solution}")
```

Resulting Cyclic Overload Ratings

This gives the cyclical overload limits as shown in table 2-4 below.

	Fixed Conditions			Cyclic Overload Factor
	K_1	t_1/t_2	θ_a	
Summer Peak Period	0.339	530/910	14.4	106.0% (95.4 MVA)
Winter Peak Period	0.395	570/870	5.69	113.5% (102.15 MVA)

Table 2-4 – Calculated Cyclic Overload Ratings

Appendix 3 - Armagh area loading

Table 3-1 details the actual and forecast loadings in MVA at each of the 33 kV substations on the Armagh area distribution network.

Substation	Demand (MVA)			
	2021 (actual)	2025 (forecast)	2029 (forecast)	2033 (forecast)
Armagh Central	10.4	11.6	12.1	13.2
Armagh North	8.5	8.2	8.4	8.7
Benburb	4.3	4.0	4.1	4.4
Keady Central	4.7	5.7	6.2	6.9
Killylea West	3.6	4.3	4.7	5.3
Markethill Central	3.7	3.7	3.8	4.1
Richill Central	5.5	5.5	5.8	6.2
Tullygoonigan	6.0	6.5	6.8	7.2
Total[10]	**46.7**	**49.4**	**51.9**	**56.0**

Table 3-1 – Actual and Forecast Loadings on 33 kV substations in Armagh area distribution network

[10] The total demand in Table 3-2 represents the sum of the peak demands at each of the substations on the Armagh area distribution network. This differs from Table 2 in the main body of this report which shows the peak demand on the network, which is lower as not all substations will experience their peak demand coincidentally.

Appendix 4 – Value of Lost Load (VoLL) Calculations

As discussed in section 3.2.2 a Value of Lost Load (VoLL) analysis has been completed using load index data of the Armagh Area 33 kV system, historic data on outages and maintenance duration for the four circuits and other assumptions. This has determined that without reinforcement the overall total cost of VoLL from faults, maintenance and during normal system operation from 2024-2064 is estimated to be £258.93m.

Figures 4-1 and 4-2 below show the total Megawatt hours (MWh) above the firm capacity (40 MVA) and the total VoLL for faults, maintenance and during normal system operation (NSO) (considering the NSO limit of 52.5 MVA). These costs will be added to the net present value analysis in the accompanying options report and are expected to have a significant impact on option 1, do nothing. As the other shortlisted options provide further capacity through the delivery of the projects this analysis will not be conducted as the need for capacity to avoid load shedding will be satisfied by the proposed solutions.

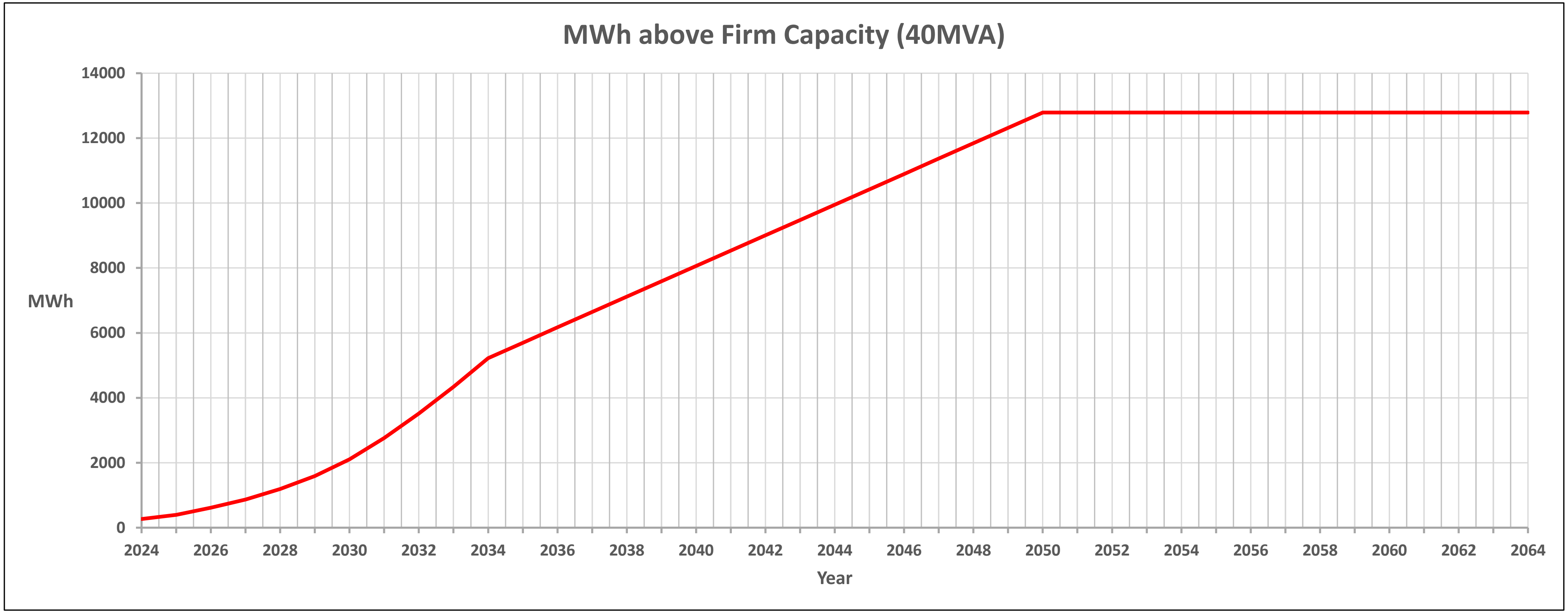

Figure 4-1 – Total MWh above firm capacity (40 MVA) of the Armagh area network

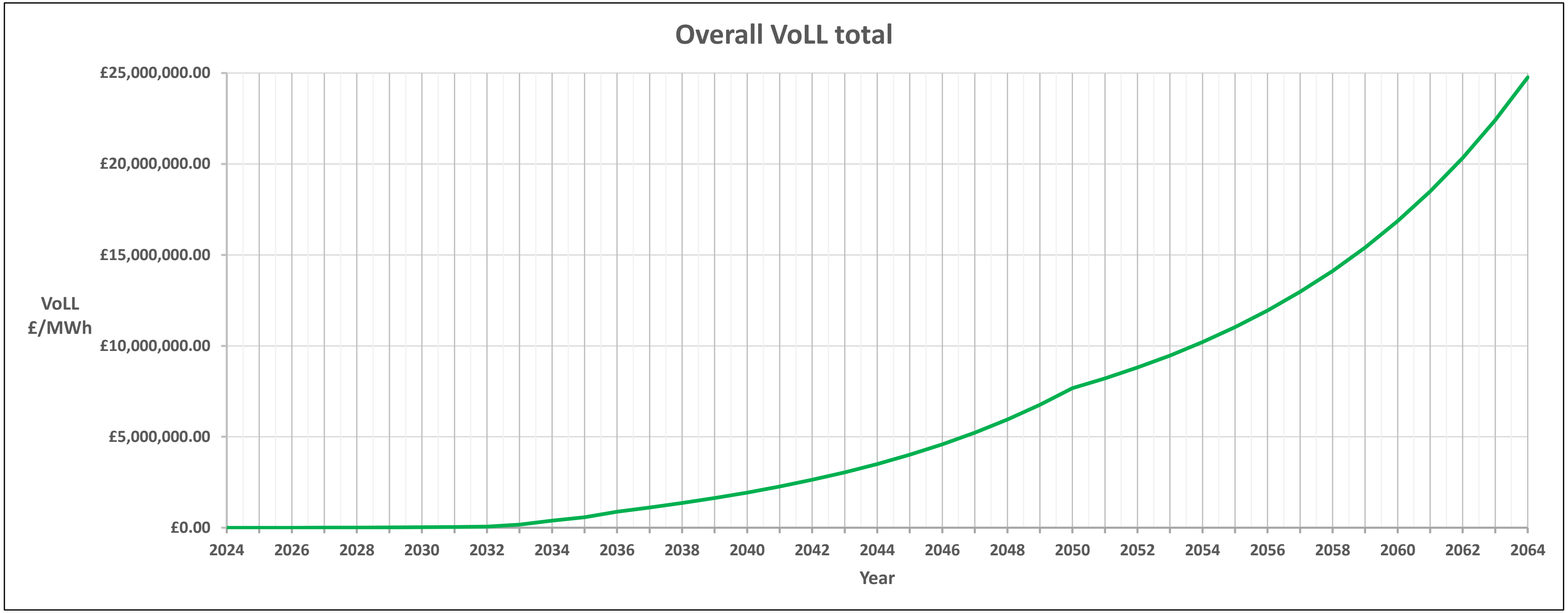

Figure 4-2 - Overall total cost of VoLL (from faults, maintenance and during normal system operation) from 2024-2064