East Tyrone

Needs Report

Date: June 2024

Castlereagh House, 12 Manse Road, Belfast BT6 9RT
Telephone: +44 28 9079 4336 • www.soni.ltd.uk

Title	Name	Signature	Date
Author	Daniel Prata		June 2023
Reviewer	Raymond Smyth	By email	June 2024
Approver	Eimear Watson	By email	June 2024

Table of contents

List of figures

List of tables

Executive summary

This Need Case appraises the current and future compliance of Dungannon Main Substation with the Transmission System Security and Planning Standards, 2015, and the Distribution System Security and Planning Standards, in particular Energy Networks Association – Engineering Recommendation P2/6, 2006 – Issue 1 (July 2006) amended for Northern Ireland in May 2015. The assessment is based on the methodology defined by Energy Networks Association – Engineering Report 130, 2014 – Issue 2, and will cover a period between 2021 and 2031.

This report includes information from demand and generation, which is available in 0. It was also needed to determine the cyclic overload ratings of the 110/33kV transformers. This process was based on IEC 60076-7:2005, Ed.1.0, Power Transformers – Part 7: Loading guide for oil-immersed power transformers, and it is described in detail in 0.

The main conclusions from this assessment are the following:

- Dungannon Main is currently compliant with the TSSPS.
- The compliance with the Standards is valid up to the end of 2026 depending on the uptake of low carbon technologies.
- Security of supply compliance does not mean that demand is always satisfied.

  This is demonstrated in Sections 3.5.4, 3.9.3 and 3.9.4 for N-1-1 Scenarios with and without distributed generation (DG) contributions.

  This can be minimised following the recommendations in the Standards by scheduling and controlling planned outages, as well to use of rotational load shedding.

  It also will help to minimise this issue if transfer capacity increases as per Table 5.

  This measure should ensure immediate transfer of capacity, since the speed to transfer capacity after N-1 scenario's inception plays a significant impact in terms of security of supply compliance.
- In an or N-1 contingency, where the contribution of the wind farm is insufficient the demand may not be satisfied after 2026 and load shedding may be required to prevent premature ageing of transformers.

  So, if demand satisfaction in these events is also required, then immediate actions are necessary to resolve these issues.

1 Introduction

A need has been identified regarding the security of supply compliance of Dungannon Main 110/33kV Substation. This substation demand is now above the nominal rating of the transformers during some periods of the day, particularly during the winter months.

The initial assessment was based on the Transmission Bulk Supply Point (BSP) Forecast Methodology 2019 provided by NIE Networks. This document forecast that demand supplied from this substation would continue to grow at a steady pace, increasing rate of growth expected due to the expected installation of Electric Vehicles Charging Points (EVCPs) and Heat Pumps (HPs).

This report will document the need for the upgrade of Dungannon Main and will form the basis of developing an Options Report with a detailed assessment of the different solutions to sort the issues identified.

2 Description of Dungannon Main

Dungannon Main 110/33kV Substation is about 3.1 km North East from Dungannon town centre.

Figure 1 shows the location of Dungannon Main 110/33kV Substation. In yellow is represented the 110kV network and in violet the 275kV network.

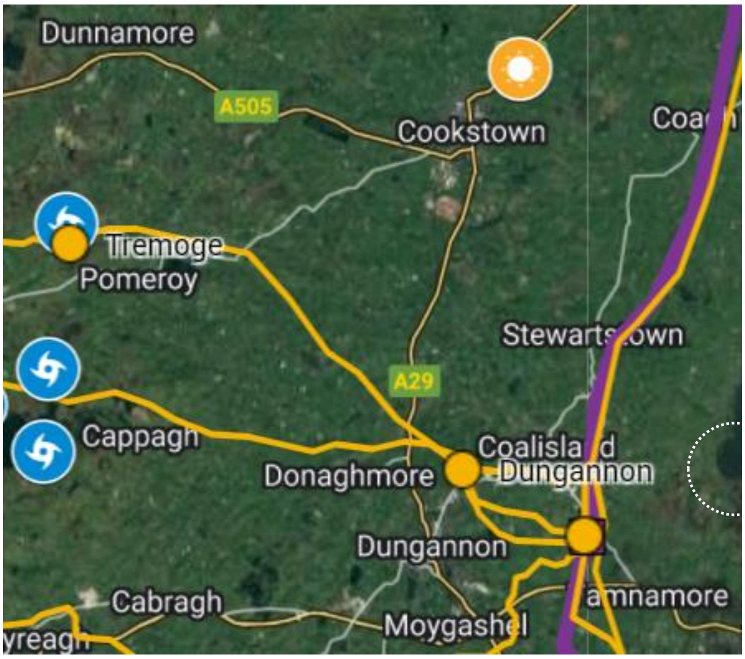


Figure 1 : Location of Dungannon Main 110kV/33kV Substation

The substation includes an eight bay 110 kV mesh configuration and two 90 MVA 110/33kV transformers. The transformers supply a 33 kV single busbar switchboard. This in turn supplies, via the 33 kV system, a number of 33/11 kV substations in Dungannon, Cookstown and Coalisland. Crockagarran Wind Farm with a capacity of 17.5 MW is also connected to the 33 kV system.

Figure 2 shows an aerial view obtained from Google Maps of Dungannon Main 110kV/33 kV substation.

Figure 2 : Dungannon Main 110kV/33kV substation

3 Security of supply assessment

The total demand at Dungannon Main has been approaching the 90 MVA of firm capacity of the site for a number of years. There is also relatively poor 33 kV resupply from neighbouring 110/33kV substations such as Omagh Main to the west, Drumnakelly Main to the east and Creagh Main to the north.

To address the load increase in the short-term, a second 33kV circuit was constructed from Creagh Main 110/33 kV substation to Coagh West 33/1 1kV. This allowed the transfer of approximately 13 MVA of demand from Dungannon Main to Creagh Main. This load relief reduced the measured demand downstream from the transformers, but it is now still above their nominal rating.

This section will go through the processes in place to perform the security of supply assessment. This assessment will require a greater understanding of demand and generation levels at Dungannon Main and how these may impact on both distribution and transmission system standards.

3.1 Standards for the security of supply assessment

Dungannon Main 110/33 kV substation includes both transmission and distribution assets.

The 110/33kV transformers are part of the transmission network, however the 33 kV transformer cables and switchboard are part of the distribution network. Therefore, standards will apply for the purpose of security of supply assessment:

- Northern Ireland Transmission System Security and Planning Standards (TSSPS), 2015.
- Distribution System Security and Planning Standards including:
  - Energy Networks Association (ENA) – Engineering Recommendation P2/6 (ER P2/6), 2006 – Issue 1 (July 2006) amended for Northern Ireland in May 2015 (ER P2/6 NI).
  - Energy Networks Association – Engineering Report 130 (EREP 130), 2014 – Issue 2.

The minimum conditions to comply with in terms of security of supply are the presented in following:

- Transmission network: TSSPS, Table 3.1 – The minimum planning supply capacity following secured events.
- Distribution network: ER P2/6 NI, Table 1 of ER P2/6 (NI) – For application in Northern Ireland.

For the transmission network, there isn't an equivalent document, so for the purpose of this assessment, and since the Group Demand (GD) [1] will not be above 300MW, EREP 130 procedure will be applied and the conclusions of the assessment will be for both networks.

The conditions to comply with at transmission and distribution are the same except if the GD is above 300MW, where the rules to apply are the ones in TSSPS[2]. On the distribution network, EREP 130 defines the procedure to conduct a security of supply assessment against ER P2/6 NI.

Figure 3 presents the assessment process as defined in EREP 130. The source of the flowchart is EREP130, Figure 5.1. The Figures and Sections refer to EREP 130.

[1] Group Demand is the estimate of the maximum demand of the group being assessed for ER P2/6 NI compliance with appropriate allowance of diversity. It can also be defined as the sum of Latent Demand and Measured Demand.

[2] This means that ER P2/6 NI and TSSPS are equal up to a GD of 300MW. Above this value, only the TSSPS rules are valid.

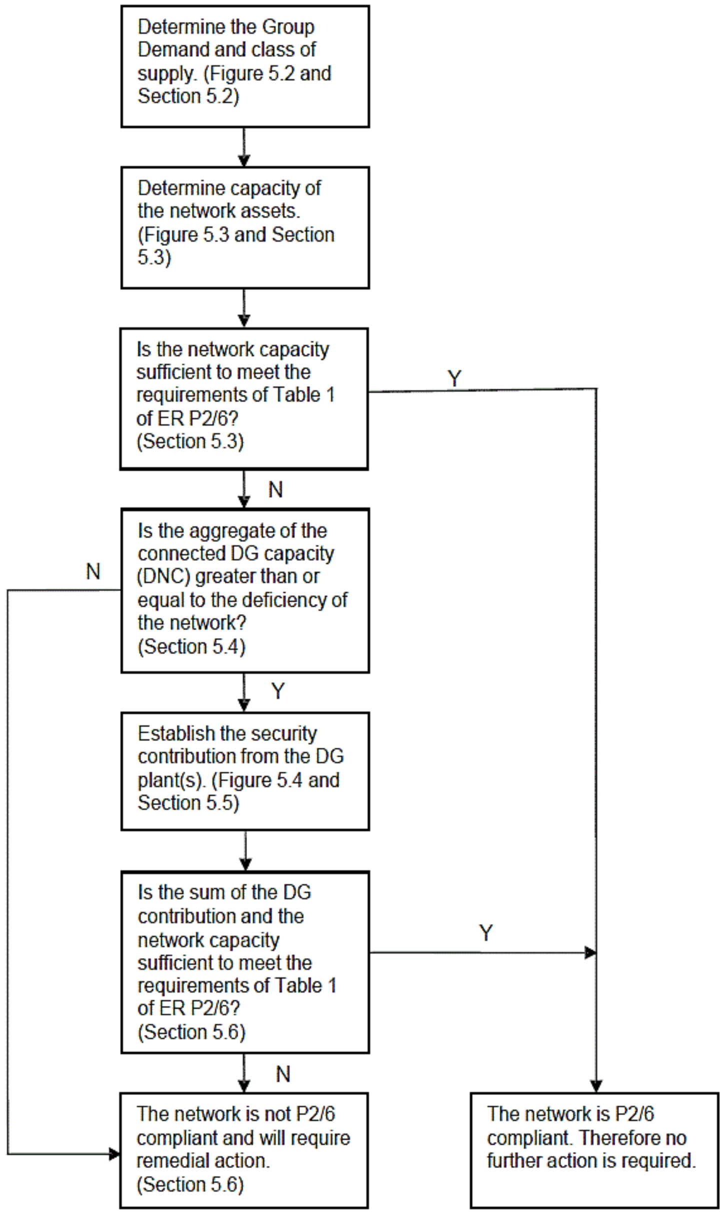


Figure 3 : Assessment process according to EREP 130

3.2 Demand Group

For the purpose of this assessment see below in Figure 4 the Demand Group[3] at Dungannon Main.

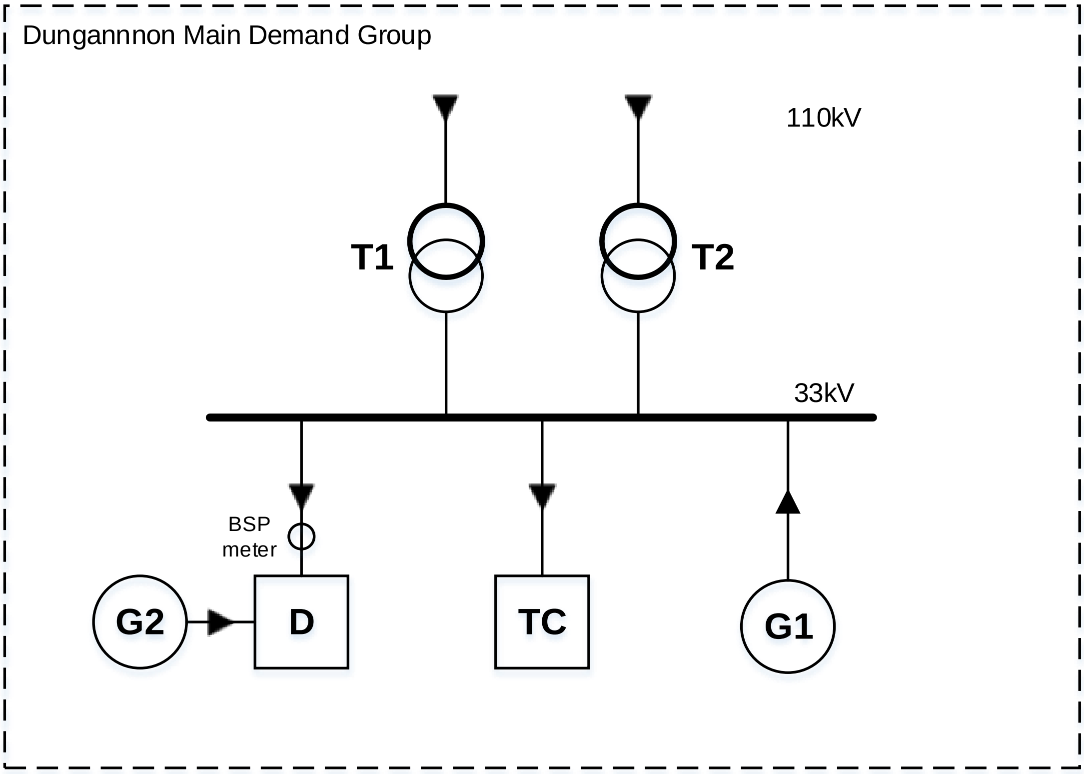
---

[3] Demand Group, according to the TSSPS, is a site or group of sites which collectively take power from the remainder of the onshore transmission system.

ER P2/6 NI and EREP 130, 2014 – Issue 2, which are in place in Northern Ireland, do not provide a definition of Demand Group.

This issue required a clarification, and ER P2/7 and EREP 130, 2019 – Issue 3, presents on Section 5 an understanding on how to define de Demand Group.

The Demand Group, in the context of ER P2/6 NI, can be identified as section or sections of the network, within the boundary of the dashed lines as presented in Figure 4, where a security of supply assessment will be carried out.



T1 and T2 : 90MVA power transformers each | G2 : Distributed Generation downstream
D : Demand | TC : Transfered Capacity | G1 : Crockagarran Wind Farm

Figure 4 : Demand Group

G2 is a representation of small-scale generation embedded in the 11kV network, and as per the information on the Transmission BSP Demand Forecast & Methodology 2019, metered data was extracted for each connected generator and added to the Bulk Supply Point Maximum Demand (BSPMD) for the base year of 2019. It was assumed that there is no reverse flow going through the BSP meter, as embedded generation G2 are Small Scale Generation (SSG) and therefore all generated power would be locally consumed.

3.3 Forecasted demand and generation

3.3.1 Demand

The forecasted BSPMD, between 2021 and 2031, is presented in Table 1[4]. Crockagarran Wind Farm, which is a large-scale generation site, is connected to the 33kV network at Dungannon Main, as a result NIEN measures the BSPMD on the outgoing feeder as seen in Figure 4[5].

---

[4] Source: Appendixes 1 and 5 of the Transmission BSP Demand Forecast & Methodology 2019 (NIEN).

[5] Transmission BSP Demand Forecast & Methodology 2019 (NIEN), Section 2.1, presents the method to meter BSP with distributed embedded large-scale generation.

Year	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
BSPMD [MVA]	101.39	101.47	101.69	102.09	102.69	103.33	104.4	104.95	105.88	107.03	107.99
BSPMD [MW][6]	97.33	97.41	97.62	98.01	98.58	99.20	100.22	100.75	101.64	102.75	103.67

Table 1 : BSPMD between 2021 and 2031

3.3.2 Generation

The generation forecast for the Demand Group is difficult to estimate as the embedded generation is mostly from renewable intermittent generation, which includes contributions from Small Scale Generation (SSG) and Large-Scale Generation (LSG), as Crockagarran Wind Farm.

For the purpose of this assessment two scenarios will be considered:

1) Conservative Scenario.

   This scenario assumes that the Maximum Export Capacity (MEC) of embedded generation will remain constant up to 2031. This provides a worst-case scenario i.e. demand is not offset by local generation.

2) Addressing Climate Change (ACC) Scenario.

   This scenario follows the Tomorrow's Energy Scenarios Northern Ireland 2020, July 2020, (TESNI2020)[7]. The aim with this scenario was to model generation under a more optimistic context that will consider of growth of Renewable Energy Sources from Electricity[8] (RES-E) connected to Dungannon Main.

0 provides details of the forecast generation at Dungannon Main between 2021 and 2031 for both scenarios above.

3.4 Group Demand and Class of Supply

To determine the Group Demand and the Class of Supply the procedure defined in EREP130, Section 4.2, will be applied.

[6] To determine the active power on the BSPMD, it was considered that the network power factor (PF) is 0.96, based on the Winter Peak Period on 2019, when this forecast was created by NIEN.

[7] SONI's TESNI2020 is built around three scenarios up to 2050 that are based on two main drivers, decarbonisation and decentralisation. The scenarios design is presented on the TESNI2020, section 3.3, page 29

[8] Also called Renewable Electricity.

3.4.1 Measured Demand and Capacity of the Downstream Generation

The values in Table 1 represent the gross demand supplied from Dungannon Main. They include the measured demand[9] and the contributions from LSG connected to the 33kV busbar, which are captured by the BSP meter as represented in Figure 2, but also from SSG which are connected downstream onto the 11kV network, as explained in the Transmission BSP Demand Forecast & Methodology 2019, Section 2.5. This accounts for demand in the demand group that is supplied by generation locally and hence is seen at the BSP meter. Note that the generation contributions represent the export capacity from the different embedded generation at the time the BSPMD occurred.

The Capacity of the Downstream Generation is given by adding the Declared Net Capability[10] (DNC) of each DG (Distributed Generation) plant, but because not all plants are exploited to the maximum of their capability, the MEC of each plant will be considered. So in Table 12 and Table 13 the capacity of the downstream generation in each scenario is given by the totals of each year, which vary from 33.56MW to 48.37MW.

EREP 130, Section 4.2, requires the Capacity of the Downstream Generation to be higher than 5% of the maximum Measured Demand, in order to identify the need to establish the contribution to the Latent Demand[11] from each DG plant.

This condition can't be verified directly as Measured Demand is unknown, but since Measured Demand is included and smaller than the BSPMD, by calculating 5% of the of the BSPMD and comparing with the Capacity of the Downstream Generation, conclusions can be made about the need to determine the Latent Demand.

It is assumed that the maximum Measured Demand occurs at the same time of the BSPMD, which is between 17:00 and 19:00, on working days, during the Winter Peak Period, and during this interval of time contributions from PV are negligible. Therefore, to suppress demand, it will have to rely on the upstream network.

The worst case occurs in 2031 in the Conservative Scenario. So, the 5% of BSPMD in 2031 (103.67MW) will equate to 5.18MW, which is lower than the Downstream Generation capacity

---

[9] Measured Demand is defined as the summated demand measured at the normal (network) in-feed points for which Group Demand is being assessed (EREP 130).

[10] Declared Net Capability is defined as the declared gross capacity of a DG plant, in MW, less the normal total parasitic power consumption attributable to that plant (EREP 130).

[11] Latent Demand is defined as demand that would appear as an increase in Measured Demand if the DG within the network (for which the Group Demand is being assessed) were not producing any output.

of 33.56MW. Following the flowchart in EREP 130, Figure 5.2, the above demonstrates that it is required to establish the contribution to the Latent Demand from each DG plant.

3.4.2 Contribution to the Latent Demand from each DG plant

To identify the contribution to the Latent Demand from each DG plant, EREP 130 presents in Section 6.6 a methodology to determine the Latent Demand. For LSG, without on-site demand, its contribution to Latent Demand is already included in the BSPMD as explained in EREP 130, Section 6.6.2.

In SSG sites (wind and CHP) there isn't information to confirm if there is on-site demand or not. However, the information about the BSPMD already includes all generation contributions and measured demand at the time the maximum demand occurred in the BSP. This means that Latent Demand of each SSG site also was captured by what was called in previous section as gross demand supplied from Dungannon Main, so there will be no need to determine the specific Latent Demand of each DG to determine de Group Demand.

3.4.3 Establish the Group Demand and determine the Class of Supply

Considering the arguments presented in previous sections, the Group Demand (GD) forecasted between 2021 and 2031 is the BSPMD, in MW, identified in Table 1 (or as called above gross demand).

Based on the GD and ER P2/6 NI, Table 1, between the years 2021 and 2031, the Class of Supply will be D, as the Range of GD is always between 60MW to 300MW. In the TSSPS similar conclusions can be taken, except that there isn't the definition of a Class of Supply.

3.4.4 Minimum demand conditions to be met following N-1 and N-1-1 scenarios

ER P2/6 NI and TSSPS have essentially the same requirements for the minimum demand conditions to be met following outages. However, some explanation of the terminology being used is required so that the wording in both Standards is not misunderstood.

N-1 scenario is referred as First Circuit Outage (FCO)[12], in ER P2/6 NI, and as 1st secured event[13] (or intact system as initial system conditions previously to the secured event), in

[12] A First Circuit Outage is a fault or an arranged circuit outage, but in classes C to F, supplies to consumers should not be interrupted by arranged outages.

[13] A secured event is a contingency which would be considered for the purposes of assessing system security and which must not result in the remaining Northern Ireland transmission system being in breach of the security criteria. Secured events are individually specified throughout the text of this Standard. It is recognised that more onerous unsecured events may occur and additional operational measures may be utilised to maintain overall Northern Ireland transmission system integrity. This includes a fault that system was designed to support or a planned circuit outage.

TSSPS. N-1-1 scenario is referred as Second Circuit Outage (SCO)[14], in ER P2/6 NI, and as 2nd secured event (or existing single planned outage as initial system conditions previously to the 2nd secured event), in TSSPS.

Note that according to EREP 130 the recommended levels of security are not intended at all times to cater for a first fault outage followed by a second fault outage, or for a simultaneous double fault outage. Nevertheless, in many instances, depending upon switching and/or loading/generating arrangements, they will do so.

This context is clearer in TSSPS as the N-1-1 scenario specifically states that applies in the situation of a single planned outage, as the case of a transformer being in maintenance (single planned outage) and the other one has a secured event (fault).

Table 2 presents the minimum demand conditions to be met following N-1 and N-1-1 scenarios from TSSPS Table 3.1.

N-1 scenario	N-1-1 scenario	
	GD≤100MW	GD>100MW
Immediately GD	Within time to restore planned outage GD	Within 3 hours Min(GD-100 MW; 1/3 of the GD)
		Within time to restore planned outage GD

Table 2 : Minimum demand to be met after N-1 and N-1-1 scenarios, over 60MW until 300MW

Note that for N-1 scenario has to secure immediately the GD, which is different from the requirements presented in ER P2/6 NI or the TSSPS.

This is because NIEN network connected downstream to Dungannon Main does not facilitate automatic disconnection of load, so the conditions used in the example in EREP 130, Section 8.2.2, d), will apply.

As per the notes in ER P2/6 NI, Table 1, a loss of supply not exceeding 60s is considered as an immediate restoration.

[14] A Second Circuit Outage is a fault followed by an arranged circuit outage.

3.5 Capacity of the network assets

3.5.1 Cyclic overload ratings of in-feed circuits

The assets that limit the in-feed circuits are the transformers, so the cyclic overload ratings for the transformers, between 2021 and 2031, is determined in 0 by application of IEC 60076-7:2005.

The transformers have the same nominal rating and have the similar cooling solutions, but they are not equal. The known data of the oldest transformer was used to determine their cyclic overload ratings. The results are presented in Table 21 and they are based on the consideration that maximum demand occurs during the Winter Peak Period, on working days, between 17:00 and 19:00.

Considering a PF=0.96, as previously used for the BSPMD calculation, Table 3, presents the cyclic overload rating, expressed in MW, for the purpose of the security of supply assessment.

Year	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
Cyclic overload rating [MVA]	99.70	99.69	99.69	99.69	99.69	99.68	99.68	99.67	99.67	99.66	99.65
Cyclic overload rating [MW]	95.71	95.70	95.70	95.70	95.70	95.69	95.69	95.68	95.68	95.67	95.66

Table 3 : Cyclic overload ratings in MW (PF=0.96)

As there are two transformers working in parallel, the capacities of each in-feeder circuit, between 2021 and 2031, are the values in Table 3.

3.5.2 Transfer capacity

Table 4 shows the information provided by NIEN about the capability of the distribution network to transfer capacity, by resupplying load typically provided by Dungannon Main from other substations in the network. For the values in MW, a PF of 0.96 was applied.

After 30min	After 3h
8MVA / 7.68MW (33kV network)	Additional 16.9MVA / 16.22MW (33kV network)
	6.6MVA / 6.34MW (11kV network)

Table 4 : Transfer capacity

The total transferred capacity is 8MVA / 7.68MW, after 30min, and 31.5MVA / 30.24MW after 3h (in aggregate). These transferred capacities are assumed to remain constant between 2021 and 2031. To minimise the impact of prolonged outages to consumers, ER P2/6 NI recommends in N-1-1 scenarios, scheduling and control of planned outages, as well the use of rotational load shedding.

In addition, it considers that "it is normal to aim for restoration of supply to 1/3 GD within 3 hours after a second circuit outage to prevent widespread and prolonged supply interruption".

Table 5 presents the difference between maximum transfer capacity within 3h of an N-1-1 scenario compared to 1/3 of GD.

Year	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
Max. transfer capacity	30.24	30.24	30.24	30.24	30.24	30.24	30.24	30.24	30.24	30.24	30.24
1/3 GD	32.44	32.47	32.54	32.67	32.86	33.07	33.41	33.58	33.88	34.25	34.56
Difference	-2.20	-2.23	-2.30	-2.43	-2.62	-2.83	-3.17	-3.34	-3.64	-4.01	-4.32

Units: MW

Table 5 : Difference between maximum transfer capacity and 1/3 of GD

It can be seen that values of transfer capacity are falling sort of the recommendation, with the values increasing as demand grows between 2021 and 2031.

3.5.3 Capacity of the network under a N-1 scenario

Under an N-1 scenario, due to fault or planned outage, the in-feed circuits between 2021 and 2031 is equal to the cyclic overload rating of the transformer presented in Table 3. Table 6 presents the network capacity on a N-1 scenario, between 2021 and 2031, according to the resupply capacity of the load normally supplied from Dungannon Main.

	Year										
Net Capacity (MW)	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
Immediate ()	-1.62	-1.71	-1.92	-2.31	-2.88	-3.51	-4.53	-5.07	-5.96	-7.08	-8.01
After 30min	6.06	5.97	5.76	5.37	4.8	4.17	3.15	2.61	1.72	0.6	-0.33
After 3h (11kV resupply)	12.4	12.31	12.1	11.71	11.14	10.51	9.49	8.95	8.06	6.94	6.01
After 3h (11kV + 33kV resupply)	28.62	28.53	28.32	27.93	27.36	26.73	25.71	25.17	24.28	23.16	22.23

Units: MW

Table 6 : Network capacity on an N-1 scenario, without DG contributions

The network capacity in a N-1 scenario in a specific year is determined by adding the cyclic overload rating of the transformers to the transfer capacity and deducting the GD.

The resupply after 3h was split between 33kV and 11kV.

Therefore, in conclusion after including for resupply available via the 11kV and 33kV, the site is expected to remain technically compliant with the TSSPS. However, there may still be a need for load shedding to prevent short term overload conditions while resupply is being arranged. It should be noted that whilst compliant technically, in practice no other substation in Northern Ireland would depend on resupply from the 33kV system in that way to achieve compliance. It should be noted that upgrades take time to deliver.

3.5.4 Capacity of the network under a N-1-1 scenario

Table 7 presents the network capacity on a N-1-1 scenario, between 2021 and 2031, considering different levels of resupply availability.

	Year										
Net capacity (MW)	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
Immediate (0MW of resupply)	-97.33	-97.41	-97.62	-98.01	-98.58	-99.2	-100.22	-100.75	-101.64	-102.75	-103.67
After 30min	-89.65	-89.73	-89.94	-90.33	-90.9	-91.52	-92.54	-93.07	-93.96	-95.07	-95.99
After 3h (11kV resupply)	-83.31	-83.39	-83.6	-83.99	-84.56	-85.18	-86.2	-86.73	-87.62	-88.73	-89.65
After 3h (11kV + 33kV resupply)	-67.09	-67.17	-67.38	-67.77	-68.34	-68.96	-69.98	-70.51	-71.4	-72.51	-73.43

Units: MW

Table 7 : Network capacity on an N-1-1 scenario, without DG contributions

In an N-1-1 scenario, when a fault following a planned outage occurs, the in-feed circuits will not be providing any energy to the Demand Group.

So, the only possibility to satisfy any demand that is not supplied by embedded generation or the in-feed circuits on Dungannon Main, will be by a resupply from other parts of the distribution network.

3.6 Security of supply networks compliance without DG contributions

3.6.1 N-1 scenario

In a N-1 scenario, security of supply requires immediate resupply of the GD less 20 MW.

Summarising, between 2021 and 2031, the Demand Group is compliant at present and could be made to continue to ensure the minimum demand is restored with a load shedding scheme.

This would trip sufficient demand to ensure that the remaining transformer is not overloaded until 33kV and 11kV transfers are carried out. It must be noted that this is not standard practice at any 110/33kV bulk supply point. This practice has been undertaken in the past however whilst a reinforcement project is being delivered.

3.7 Assessing the potential contribution of DG to the security of supply

The network assets are sufficient to ensure the security of supply, albeit with the necessary introduction of a demand disconnection scheme. For completeness however it is also useful to assess if the contributions of all DG connected has the potential to defer the need for a demand disconnection scheme.

Because not all plants are exploited to the maximum of their capability, the MEC of each plant will be considered, instead of the DNC. Table 12 and Table 13 present the total MEC for the Conservative and the ACC Scenarios for generation.

By comparing the total MECs for each year, it can be concluded that there is potential for the connected DG to contribute to the security deficiencies, as the total MEC, regardless of the scenario, is always higher than the level of a demand disconnection scheme. To identify this potential further analysis will be conducted in the next sections.

3.8 Contributions of DG plants to the security of supply

The process to assess the DG plants contribution to the security of supply is described in detail in EREP 130, Section 4.5.

3.8.1 Assessing the contributions from the DG plants

To assess the contributions from the DG plants the de-minimis test described in EREP 130, Section 4.5.1 and Section 6.5, ii, will be applied. The recommendation is that only plants which their DNC is equal to or above 5% of the GD, with a minimum of 100kW, are to be considered for their contribution for security of supply. For the purpose of this assessment the MEC will be used instead of the DNC as previously explained. Applying 5% to the GD it can be seen that it varies between 4.87MW in 2021 and 5.18MW in 2031.

Looking to 0, only the large scale wind technology, which is Crockagarran Wind Farm, meets the de-minimis threshold with 17.5MW, between 2021 and 2031. This represents 17.98% in 2021 and 16.88% in 2031. The small-scale wind and CHP plants at this node have individual capacities below this 5% threshold with the MEC values presented in this report being the aggregate of several plants, according to their technology.

3.8.2 Assessing the ride through capability of the DG plants

If a fault occurs it is necessary to know how the DG plant protection will react so that the contribution of the plant for the security of supply can be assessed. From the Wind Farm Power Stations (WFPS) Settings Schedule[15], Section 5.9, Fault Ride Through, and SONI Grid Code, CC.S2.2.3.3 (a), the Crockagarran Wind Farm shall[16] remain connected to the Distribution Network in the event of a fault according to CC.S2.2.3.3.

3.8.3 Establishing the contribution of each DG plant to the security of supply

EREP 130, Section 5, provides three Approaches to assess the contribution of each DG plant to the security of supply. The simplest method of assessment is Approach 1 and is going to be applied based on the following:

- Wind farms are one of the technologies covered in EREP 130, Tables 2-2.
- It is assumed that the average availability of the Intermittent Generation[17] (Crockagarran Wind Farm) under consideration is not significantly different from that used to produce EREP 130, Tables 2-2.

As a condition to establish the contribution of the wind farm, it is also going to be considered that in the event of an N-1 scenario, the plant will remain connected and feeding demand. To apply Approach 1 it is required to know the Persistence[18] (T_m) of the wind farm. However, there isn't information available about this parameter, so the following cases are going to be considered:

1. The wind farm has the capacity to provide continuity of supply in the time between the inception of this scenario and the time when the first batch of 7.68MW can be transferred on the 33kV network. From EREP 130, Table 2-2A, with a T_{m1}=30min, the F factor is 28%. The security contribution is therefore 4.90MW.
2. The wind farm has the capacity to provide continuity of supply in the time between the start of this scenario and the time when the batch of 6.34MW can be transferred on the 11kV or 16.22MW can be transferred on the 33kV network. In this case after 30min the 7.68MW are confirmed as resupplied from other substations. From EREP

[15] http://www.soni.ltd.uk/media/documents/Operations/Grid-Code/SONI-GridCodeWFPS-SettingsScheduleVersion6-31-07-2015.pdf.

[16] According to SONI's records Crockagarran Wind Farm was connected to the Distribution Network in September 2010 or later.

[17] Intermittent Generation is a generation plant where the energy source of the prime mover can't be made available on demand.

[18] Persistence is the minimum time for which output from an Intermittent Generation must be continuously available for it to be considered as contribute to securing the GD.

130, Table 2-2A, with a T_{m2}=3h, the F factor is 24%. The security contribution is 4.20MW.

Note that this case it is in line with the values in EREP 130, Table 2-4 for switching in D Demand Classes[19].

Only these cases are considered as after 3h the capacity transferred is sufficiently high to ensure that there are no security of supply issues, without DG contributions, as can be seen in Section 3.6.

3.8.4 Checking for dominance of the in-feed circuits and common mode failures

EREP 130, Sections 4.5.4 and 6.3, provides guidance for checking for dominance of the in-feed circuits. The objective of checking for dominance of the in-feed circuits is to ensure that demand satisfaction is not put in excessive risk from the loss of a DG plant.

In order to apply this principle, it might be necessary to limit the contributions from DG by imposing DG contribution caps. As only Crockagarran Wind Farm contribution is considered, the criteria to verify dominance of the in-feed circuits is achieved by validating the following inequality:

$$C_g \leq \frac{C_{c1}}{F_{N_1} \times N_1} \qquad [MW] \qquad [1]$$

Where:

C_g is DNC of each DG unit, in MW. In this assessment the MEC will be used.

C_{c1} is the capacity of largest circuit, in MW. In this case the circuit is limited by the transformer cyclic rating.

N_1 is the number of DG units equivalent to a N-1 scenario, as specified in EREP 130, Table 2-3.

F_{N_1} is F factor applied to the N_1largest DG units, in %. In this assessment the two cases considered in Section 3.8.3 will have to be verified.

Knowing that:

- $C_g = 17.5MW$, regardless of the scenario in 0, between 2021 and 2031.

[19] This represents the worst case in the report from UMIST, "Developing the P2/6 Methodology", Section 2.6.2.3, page 55. Report number DG/CG/00023/REP (URN 04/1065).

- $95.66MW \leq C_{c1} \leq 95.71MW$, as per Table 3.
- $F_{N_1} = 28\%$ or $F_{N_1} = 24\%$, as per the case assessed in Section 3.8.3.
- $N_1 = 1$. For Intermittent Generation this parameter is assumed to be 1 regardless of the situation because the DNC (in this case the MEC) used to determine the contribution to the system security relates to the complete plant.

So, replacing values in Inequality [1], it is verified the dominance of the in-feed circuits, and no capping of the DG plant is required. Common mode failures verifications do not apply in this context as only one DG plant is considered relevant for this assessment.

3.9 Security of supply networks compliance with DG contributions

Based on the two cases defined in Section 3.8.3, the security contributions are the following:

1. 4.90MW, if the wind farm has the capacity to provide continuity of supply in the time between the inception and 30min, and after it is possible to resupply 7.68MW.
2. 4.20MW, if the wind farm has the capacity to provide continuity of supply in the time between the inception and 3h, and after it is possible to resupply 7.68MW + 6.34MW + 16.22MW, a total of 30.24MW.

3.9.1 N-1 scenario (Case 1)

Table 8 presents, for a N-1 scenario, Case 1, the Demand Group deficit and surplus of capacity with DG contribution.

	Year										
Net capacity (MW)	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
Immediate (0MW of resupply)	3.28	3.19	2.98	2.59	2.02	1.39	0.37	-0.17	-1.06	-2.18	-3.11
After 30min	6.06	5.97	5.76	5.37	4.8	4.17	3.15	2.61	1.72	0.6	-0.33
After 3h (11kV resupply)	12.4	12.31	12.1	11.71	11.14	10.51	9.49	8.95	8.06	6.94	6.01
After 3h (11kV + 33kV resupply)	28.62	28.53	28.32	27.93	27.36	26.73	25.71	25.17	24.28	23.16	22.23

Units: MW

Table 8 : Network capacity on an N-1 scenario, with DG contributions (Case 1)

Security of supply is only achievable until 2027, after that it the remaining transformer would be loaded in excess of its cyclic rating. Nevertheless, counting on 33kV and 11kV resupply there is 22.23MW of headroom after 3 hours. The site could be made to remain in compliance with a demand disconnection scheme which would trip a small amount of demand and prevent transformer overload whilst the 33kV and 11kV switching is underway. This is very rarely used and only in such cases where a reinforcement scheme is being progressed.

3.9.2 N-1 scenario (Case 2)

Table 9 presents, for a N-1 scenario, Case 2, the Demand Group deficit and surplus of capacity with DG contribution.

	Year										
Net capacity (MW)	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
Immediate (0MW of resupply)	2.58	2.49	2.28	1.89	1.32	0.69	-0.33	-0.87	-1.76	-2.88	-3.81
After 30min	10.26	10.17	9.96	9.57	9	8.37	7.35	6.81	5.92	4.8	3.87
After 3h (11kV resupply)	12.4	12.31	12.1	11.71	11.14	10.51	9.49	8.95	8.06	6.94	6.01
After 3h (11kV + 33kV resupply)	28.62	28.53	28.32	27.93	27.36	26.73	25.71	25.17	24.28	23.16	22.23

Units: MW

Table 9 : Network capacity on an N-1 scenario, with DG contributions (Case 2)

Note that in this case the contribution of the DG will be extended for 3h, so it will add up to the load transfer that will be guaranteed after 30min. Security of supply is only achievable until 2026 for an N-1 scenario, after that it will require a demand disconnection scheme to prevent exceeding the transformer cyclic rating until reinforcement is implemented.

3.9.3 N-1-1 scenario (Case 1)

Table 10 presents, for a N-1-1 scenario, Case 1, the Demand Group deficit and surplus of capacity with DG contribution. In this scenario there is always deficit of capacity in the Demand Group, but that does not mean that the minimum demand criteria to ensure security of supply are not fulfilled. So, under a N-1-1 scenario, there are two different criteria to assess the security of supply, as GD becomes higher than 100MW in 2027.

	Year						
Net capacity (MW)	2021	2022	2023	2024	2025	2026	2027
Immediate (0MW of resupply)	-92.43	-92.51	-92.72	-93.11	-93.68	-94.3	-95.32
After 30min	-89.65	-89.73	-89.94	-90.33	-90.9	-91.52	-92.54
After 3h (11kV resupply)	-83.05	-83.13	-83.34	-83.73	-84.3	-84.92	-85.94
After 3h (11kV + 33kV resupply)	-66.83	-66.91	-67.12	-67.51	-68.08	-68.7	-69.72

Units: MW

Table 10 : Network capacity on an N-1-1 scenario, with DG contributions (Case 1)

This assessment requires the analysis of two different contexts:

1) The immediate response of the Demand Group to satisfy the minimum demand.
2) The capability of the Demand Group to satisfy GD following the restoration of a planned outage.

The first context, which only applies in 2027, within the first 3h following the N-1-1 scenario, it needs to satisfy a load of GD-100MW, which is 0.22MW. The contribution of the DG from the N-1-1 scenario's inception to 30min will ensure 4.90MW. After 30min up to 3h, the DG contribution will stop, but the resupply of 7.68MW will be in place.

In summary, looking to Table 10 can be misleading as it refers to the satisfaction of all demand, but during the first 3h following the N-1-1 scenario's inception, the criterion is different and therefore the minimum demand within 3h can be fulfilled.

The second context applies from 2021 to 2026, with GD equal or below 100MW, and in 2027 after 3h of N-1-1 scenario's inception. The criterion of minimum demand is to guarantee GD within time to restore a planned outage.

This context requires the Demand Group to satisfy this condition immediately, which corresponds to the minimum demand requirements in the N-1 scenario.

Looking to Table 8, there is a sufficient capacity between 2021 and 2027, regardless of the context in terms of resupply. Therefore, it is demonstrated that in an N-1-1 scenario, with the DG contributions, the Demand Group also fulfils the requirements in terms of minimum demand, as in the N-1 scenario, which means that it is compliant in terms of security of supply between 2021 and 2027.

3.9.4 N-1-1 scenario (Case 2)

Table 11 presents, for a N-1-1 scenario, Case 2, the Demand Group deficit and surplus of capacity with DG contribution. Between 2021 and 2026, in an N-1-1 scenario, GD is always equal or lower than 100MW, so the GD has to be guaranteed immediately after the restoration of a planned outage, as in the N-1 scenario.

Looking to Table 9 it is possible to confirm that this requirement can be fulfilled. So, the Demand Group will be compliant in terms of security of supply from 2021 until 2026, but in 2027 and onwards, remedial actions will have to be in place to ensure security of supply compliance.

	Year					
Net capacity (MW)	2021	2022	2023	2024	2025	2026
Immediate (0MW of resupply)	-93.13	-93.21	-93.42	-93.81	-94.38	-95
After 30min	-85.45	-85.53	-85.74	-86.13	-86.7	-87.32
After 3h (11kV resupply)	-83.05	-83.13	-83.34	-83.73	-84.3	-84.92
After 3h (11kV + 33kV resupply)	-66.83	-66.91	-67.12	-67.51	-68.08	-68.7

Units: MW

Table 11 : Network capacity on an N-1-1 scenario, with DG contributions (Case 2)

4 Conclusions

This assessment was able to provide evidence to justify the need to take remedial actions in order for Dungannon Main 110/33kV Substation to comply with the TSSPS and ER P2/6 NI Security of Supply Standards.

The Substation is presently compliant in terms of security of supply with the Standards up to 2026. After this, a demand disconnection scheme would have to be in installed so that the Substation can continue to comply with the Security of Supply Standards applied in this document. In Northern Ireland security of supply using demand disconnection scheme are generally only used as an interim measure whilst more permanent reinforcement is implemented. This scheme would be installed as a temporary measure until reinforcement is implemented.

Crockagarran Wind Farm shall remain connected to the Distribution Network in the event of a fault, and according to the Energy Networks Association – Engineering Report 130, 2014 – Issue 2, Table 2-4, for switching in D Demand Classes, the Persistence are 3h.

This Persistence period of the Wind Farm will ensure sufficient time for the Distribution Network to transfer capacity and guarantee compliance with the Standards. This windfarm would help in the event of an n-1 to avoid the load shedding scheme from operating during an n-1.

Another conclusion of the assessment is that the recommended 1/3 of GD is not met for the N-1-1 contingency, as per Table 5. This could be minimised following the recommendations in ER P2/6 NI, Table 1's notes, for N-1-1 scenarios, by scheduling and controlling planned outages.

In conclusion the N-1 contingency is expected to require manual transfer of demand over a 3-hour period to maintain compliance. This is expected to require a demand disconnection scheme to prevent a transformer overload condition whilst 33kV and 11kV switching is undertaken. However, a scheme like this, whilst allowing compliance to be retained, would result in some disruption to supplies and is not a long-term solution. This has been used as a temporary measure in the past but currently no other 110/33kV substation in Northern Ireland requires this. Ultimately reinforcement of the bulk supply point at Dungannon is required.

Appendix A - Generation forecast

Below are presented the assumptions and considerations for the generation forecast, and present the estimates for the two scenarios considered for security of supply assessment.

The information from existing embedded generation comes from information provided by NIE Networks.

Assumptions and considerations

This section presents assumptions and considerations for the values forecasted of the two scenarios for large- and small-scale generation.

Large scale wind

The MEC for large scale wind plants is expected not to increase during this period regardless of the scenario.

The reason for this behaviour is because NIEN prioritise the clustering of generator, particularly onshore wind farms, so that they can share the network infrastructure for connection purposes.

Only where there is insufficient potential generation in an area to justify a cluster, then generators would continue to be connected on an individual basis to the 33kV system[20].

The MEC considered refers to 2020.

Small-scale wind

Small scale wind growth for the ACC Scenario will follow the forecasts that were considered in TESNI2020 for Dungannon Main.

Micro and small-scale PV

Micro[21] and small-scale PV are technologies that play an important role in terms of embedded generation in Dungannon Main.

---

[20] This policy is in the Statement of Charges for Connection to Northern Ireland Electricity Networks Distribution System, 15th July 2020, Version 1.2, section 7, and Appendix 2 (Methodology for Connecting Groups of Generators to the Northern Ireland Distribution System using Cluster Substations)

[21] This includes PV generation under EREC G83 and EREC G98/NI.

However, the periods that the BSPMD occur in Dungannon Main are during the Winter Peak Period[22], typically between 17:00 and 19:00, when tea takes place. This means that PV contribution in these periods will be very reduced or null.

In this context of analysis, generation contributions are only relevant at the time the BSPMD occurs, so for this purpose micro and small-scale PV contributions will be considered null.

Small-scale Combined Heat and Power

Small scale Combined Heat and Power (CHP)[23] technology based embedded generation growth connect to Dungannon Main is unknown and TESNI2020 does not provide any information. Many of these plants were built to capture the benefits of the Renewable Obligation scheme through the Renewable Obligation Certificates that were issued to generators.

However, this scheme came to closure on the 31st March 2017 for these technologies, which meant that it became less interesting to invest on these solutions[24]. Taking an approach by the safety side, it is going to be considered that MEC from this technology will maintain its values regardless of the scenario. The MEC considered refers to 2020.

Others

Contributions from small scale mixed aggregated sites[25] and small-scale hydro[26] will be neglected under this assessment as they represent a very small percentage of the embedded generation connected to Dungannon Main. This consideration will play on the safety side of this analysis as they will not contribute for the export capacity in Dungannon Main.

Conservative Scenario forecast

Table 12 presents the forecasted MEC for the Conservative Scenario between 2021 and 2031 for the relevant RES-E based technologies connected to Dungannon Main.

---

[22] January, February, November and December.

[23] Small scale CHP includes spark ignition engines from sewage treatment works, anaerobic digestion (AD), landfill gas (LFG) plants and other small-scale biogas-based plants.

[24] https://www.ofgem.gov.uk/environmental-programmes/ro/about-ro/ro-closure.

[25] Small-scale mixed aggregated sites include cases of anaerobic digestion (AD), wind or PV together. All these sites combined had in 2020 a MEC of 1.39MW.

[26] Small scale hydro in Dungannon Main was 0.09MW in 2020.

Year	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
Large scale wind	17.50	17.50	17.50	17.50	17.50	17.50	17.50	17.50	17.50	17.50	17.50
Small scale wind	9.26	9.26	9.26	9.26	9.26	9.26	9.26	9.26	9.26	9.26	9.26
Small scale CHP	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.80
Totals	33.56	33.56	33.56	33.56	33.56	33.56	33.56	33.56	33.56	33.56	33.56

Units: MW

Table 12 : MEC for the Conservative Scenario between 2021 and 2031

Addressing Climate Change Scenario forecast

Table 13 presents the forecasted MEC for the ACC Scenario between 2021 and 2031 for the relevant RES-E based technologies connected to Dungannon Main.

Year	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
Large scale wind	17.50	17.50	17.50	17.50	17.50	17.50	17.50	17.50	17.50	17.50	17.50
Small scale wind	10.86	12.47	14.08	15.68	17.29	18.64	20.00	21.35	22.71	24.06	24.07
Small scale CHP	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.80
Totals	35.16	36.77	38.38	39.98	41.59	42.94	44.3	45.65	47.01	48.36	48.37

Units: MW

Table 13 : MEC for the Addressing Climate Change Scenario between 2021 and 2031

Appendix B - Cyclic overload ratings of transformers

This appendix aims to estimate the cyclic overload ratings of the oil-filled power transformers installed in Dungannon 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, which also will be referred on this appendix as the Standard.

The principles used in this methodology are the following:

- The transformers should operate in on a normal cyclic loading[27];
- Cycles take 24h (or 1440min), as per the evolution of demand in the substation;
- No loss-of-life during each cycle;
- 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

The typical demand profiles in Dungannon Main on a working day with maximum demand on the Summer Peak Period and the Winter Peak Period are presented, respectively, in Figure 5 and Figure 6[28].

It can be seen that the measured demand has a cyclic behaviour of 24h that translates the mixed residential and commercial background of the demand in Dungannon Main, with a peak

[27] 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".

[28] These demand profiles were base based on data from 2017.

during tea, typically between 17:00 and 19:00, which is more evident during the Winter Peak Period.

The theoretical measured demand curves were defined in order to maximise the correlation coefficients (R).

Both profiles present very high correlation coefficients (R), which demonstrates that both theoretical measured demand profiles, present a strong positive linear correlation with the measured demand profile[29].

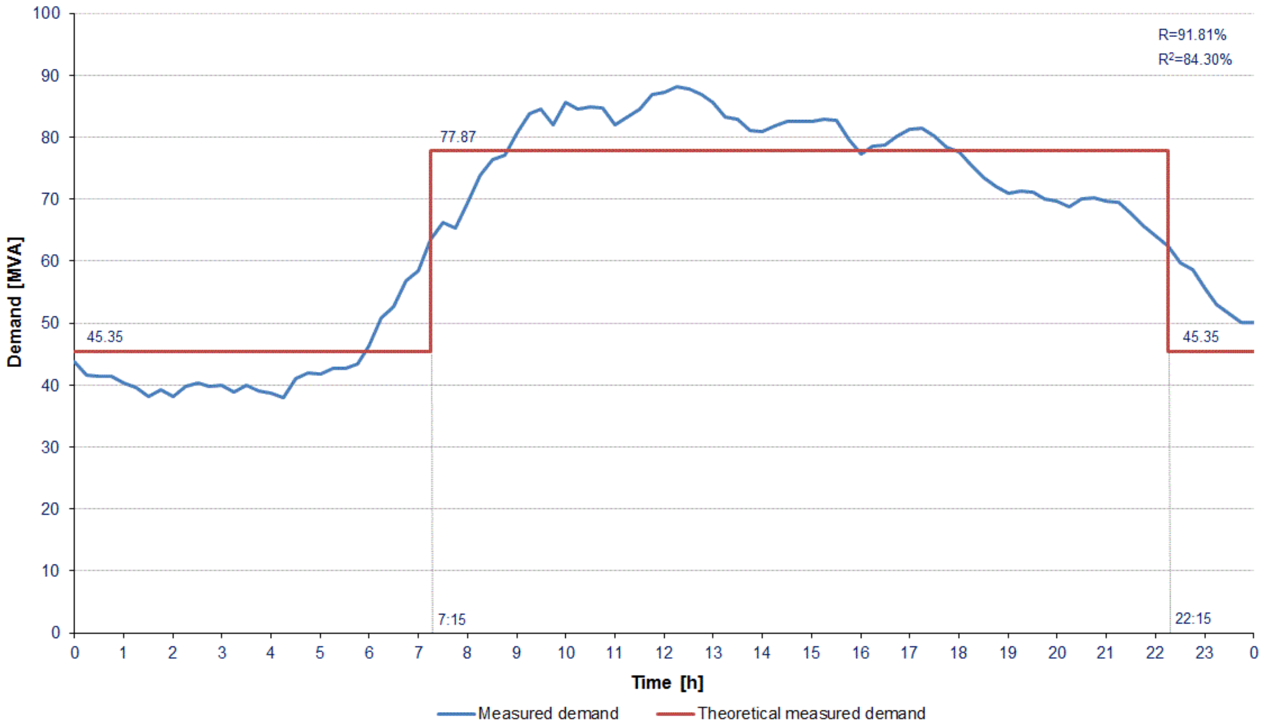


Figure 5 : Typical demand profile on a working day with maximum demand (Summer Peak Period)

[29] https://internal.ncl.ac.uk/ask/numeracy-maths-statistics/statistics/regression-and-correlation/strength-of-correlation.html#Correlation Coefficients

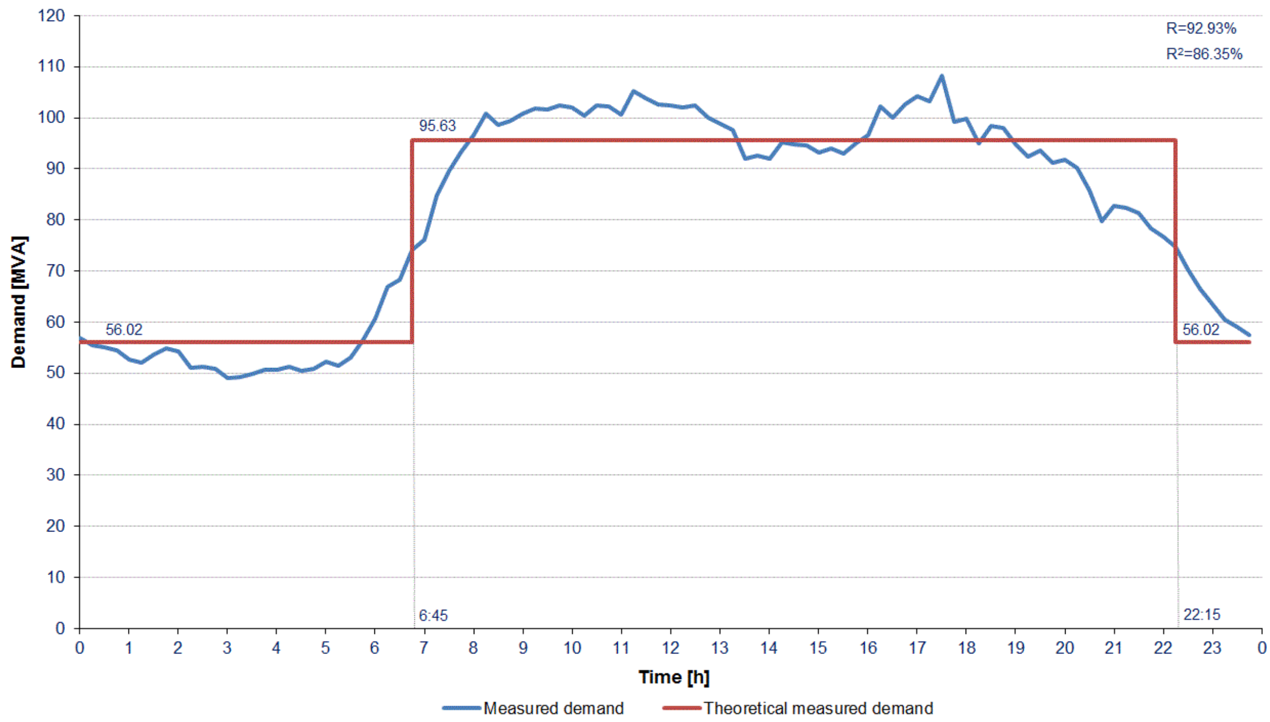


Figure 6 : Typical demand profile on a working day with maximum demand (Winter Peak Period)

Also, the coefficients of determination (R^2) of both profiles are very high, which means that the variations of the measured demand are accounted by the theoretical measured demand in more than 84% of the times.

The theoretical measured demands are used to apply the Standard to determine the cyclic overload factors.

As it can be seen from the theoretical measured demand there is a lower and a higher step, which were determined based on the average measured demand during those periods.

To determine the cyclic overload factors, the lower step will be independent variables, and these values of 45.35MVA for the Summer Peak Period, and 56.02MVA for the Winter Peak Period, will be considered as they will allow to determine the maximum cyclic overload factors that can be applied to a power transformer in a N-1 scenario.

Therefore, the load factors to be considered during the lower step of the theoretical measured demand (K_1) are the following:

- Summer Peak Period: $K_1 = 45.35MVA/90MVA = 0.50p.u.$.
- Winter Peak Period: $K_1 = 56.02MVA/90MVA = 0.62p.u.$.

The time relation between the lower step and the higher step (t_1/t_2)[30] can be attained from the theoretical demand profiles:

- Summer Peak Period: $t_1/t_2 = 9/15$.
- Winter Peak Period: $t_1/t_2 = 8.5/15.5$.

The limitation on the cyclic overload factor for a transformer depends on several factors. But 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[31] 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.

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

, 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].

---

[30] t_1 is the time duration of the lower step on a 24h cycle, in hours. t_2 is the time duration of the higher step on a 24h cycle, in hours.

[31] The hotspot is considered the hottest spot of the windings.

$$L = \int_{t_1}^{t_2} V dt \qquad [min] \qquad [3]$$

, where

t_1 and t_2 are the initial and the end loss-of-life time, in min.

Hot-spot and top-oil temperatures

According to the standard there are two ways to describe the hot-spot and the top-oil[32] temperatures as function of time.

The approach taken will be based on the exponential equations' solutions described in Section 8.2.2 of the Standard, which are solutions of the differential equations that model the thermal behaviour of the transformer[33].

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 Dungannon 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 models the temperature behaviour for the lower and higher steps[34] of the load factor[35], respectively:

$$\theta_h(t) = \theta_a + \Delta\theta_{or}.\left(\frac{1+R.K^2}{1+R}\right)^x + \left[\Delta\theta_{oi} - \Delta\theta_{or}.\left(\frac{1+R.K^2}{1+R}\right)^x\right].f_3(t) + H.g_r.K^y \qquad [°C] \qquad [4]$$

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

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

[34] 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.

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

$$\theta_h(t) = \theta_a + \Delta\theta_{oi} + \left[\Delta\theta_{or}.\left(\frac{1+R.K^2}{1+R}\right)^x - \Delta\theta_{oi}\right].f_1(t) + \Delta\theta_{hi} + (H.g_r.K^y - \Delta\theta_{hi}).f_2(t) \qquad [°C] \qquad [5]$$

, where

θ_a 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 K (or °C).

H is the hot-spot factor, dimensionless.

g_r 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]:

$$f_1(t) = 1 - e^{\frac{-t}{k_{11}.\tau_o}} \qquad [\,] \qquad [6]$$

$$f_2(t) = k_{21}.\left(1 - e^{\frac{-t}{k_{22}.\tau_w}}\right) - (k_{21} - 1).\left(1 - e^{\frac{-t}{\tau_o/k_{22}}}\right) \qquad [\,] \qquad [7]$$

$$f_3(t) = e^{\frac{-t}{k_{11}.\tau_o}} \qquad [\,] \qquad [8]$$

, 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 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:

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

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

Equations [4] to [10] were defined in the 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 used in the Standard, 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]:

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

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

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

For medium size power transformers with ONAF cooling , the recommended thermal characteristics for the exponential equations are presented in Table 14.

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	21.96	$R = Load\ losses\ at\ rated\ current/No-load\ losses$. From the older transformer nameplate $R = 702.70kW/32kW = 21.96$
Average-winding-to-average-oil temperature gradient at rated current, in K (or °C)	g_r	22.76	Extrapolated from data in IEC 60076-7:2005, Sections 8.1.3, for 120kV and 410kV 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)	$\Delta\theta_{or}$	52	Adopted from example in IEC 60076-7:2005, Table E.1.

Table 14 : Characteristics related to the loadability of the transformer

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 [11] and [12], and the hot-spot temperature rise above top-oil temperature in the tank at rated current ($\Delta\theta_{hr}$), 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 IEC 60076-7:2005, Table E.1 example.

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 in 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 dependable of the transformer physical characteristics, it has a separate treatment.

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

To avoid getting the transformer overheated by oversizing the cyclic overload factors, it will be considered the average for the Winter and Summer Peak Periods, of the monthly mean of daily maximum air temperatures, between 2001 and 2020.

The information was obtained from the Met Office National Climate Information Centre[36] database.

The values of the air temperature to be considered on this assessment are the following:

- Summer Peak Period: $\theta_a = 17.36°\mathrm{C}$.
- Winter Peak Period: $\theta_a = 8.13°\mathrm{C}$.

Limits on a normal cycling loading

The current and temperature limits applicable to normal cycling loading[37] in medium power transformers are presented in Table 15.

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

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

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

Table 15 : Limits applicable to normal cycling loading

Initial conditions

On Figure 7 is presented a typical theoretical demand profile split in lower and higher steps, respectively the left and right graphs.

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

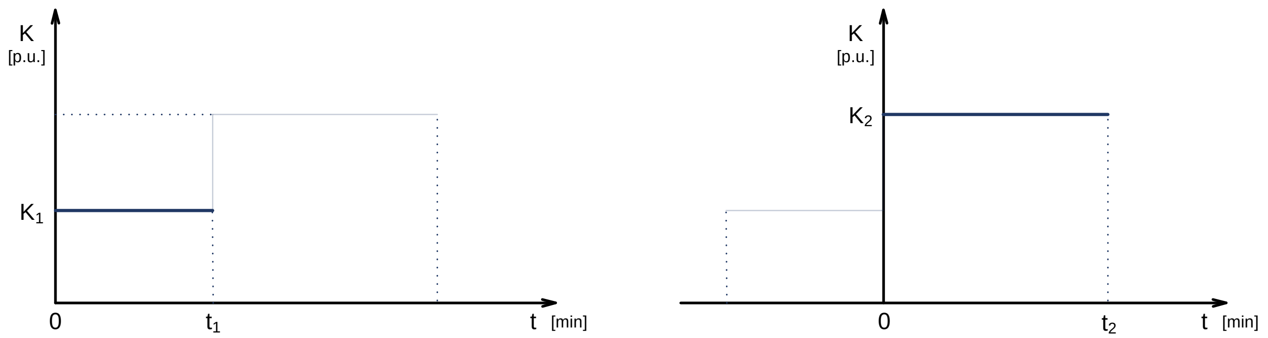


Figure 7 : Typical theoretical demand profile split in lower and higher steps

A cycle takes a day or 1440min.

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 it will be in steady state.

So, when it occurs a change of load factor, the initial conditions are the following:

- Descendent flank (lower step):

  $\theta_h(t)$ and $\theta_o(t)$ behaviours in $0 \leq t < t_1$ are explained by Equations [4], [8] and [9], so $\Delta\theta_{oi}(0)$ has to be calculated.

  Since $\Delta\theta_{oi}$ can be written as $\Delta\theta_{oi} = \theta_{oi} - \theta_a$ and the thermal system is assumed to be in steady-state ($\frac{d\theta_o(t)}{dt} = 0$), then $\Delta\theta_{oi}(t_0^-) \cong \Delta\theta_{or}.\left(\frac{1+R.K_2{}^2}{1+R}\right)^x = \Delta\theta_{oi}(t_0)$ as $(f_1(0^-) \to 1)$.

- Rising flank (higher step):

  $\theta_h(t)$ and $\theta_o(t)$ behaviours in $0 \leq t < t_2$ are explained by Equations [5], [6], [7] and [10], so $\Delta\theta_{oi}(0)$ and $\Delta\theta_{hi}(0)$ have to be calculated.

  Using Equations [8], [9] and [11] with $t = t_1^-$ and $K = K_1$, $\theta_o(0^-) = \theta_a + \cdots$

  $\cdots\ \Delta\theta_{or}.\left(\frac{1+R.K_1^2}{1+R}\right)^x + \left[\Delta\theta_{oi}(t_0) - \Delta\theta_{or}.\left(\frac{1+R.K_1^2}{1+R}\right)^x\right].f_3(0^-)$.

  It is assumed that the thermal system is in steady-state $(f_3(t_1^-) \to 0)$, therefore, using Equation [11], $\Delta\theta_{oi}(0^-) \cong \Delta\theta_{or}.\left(\frac{1+R.K_1{}^2}{1+R}\right)^x = \Delta\theta_{oi}(0)$

  Using Equations [4], [8], [9], and [12], then $\Delta\theta_{hi}(0^-) = H.g_r.K_1^y = \Delta\theta_{hi}(0)$.

In Table 16 is presented the resume of the initial conditions in the beginning of each step.

	Lower step	Higher step
$\Delta\theta_{oi}$	$\Delta\theta_{or}.\left(\frac{1+R.K_2^2}{1+R}\right)^x$	$\Delta\theta_{or}.\left(\frac{1+R.K_1^2}{1+R}\right)^x$
$\Delta\theta_{hi}$	----------	$H.g_r.K_1^y$

Table 16 : Resume of initial conditions in the beginning of each step

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 transformer does not accelerate ageing, but at the same time the overload capacity is exploited during periods of cyclic normal loading the loss-of-life (Expression [3]) as to respect the below relation, for a daily cycle:

$$L(t,K_2) = L_1(t,K_2) + L_2(t,K_2) = \int_0^{t_1} V_1\big(\theta_{h1}(t,K_2)\big)dt + \int_0^{t_2} V_2\big(\theta_{h2}(t,K_2)\big)dt = 1440 \qquad [13]$$

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

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

Changing values in the initial conditions, Table 16 will have the following values for Summer and Winter Peaks:

	Summer Peak Period		Winter Peak Period	
	Lower step	Higher step	Lower step	Higher step
$\Delta\theta_{oi}$	$4.24 \times (1 + 21.96 \times {K_2}^2)^{0.8}$	18.92	$4.24 \times (1 + 21.96 \times {K_2}^2)^{0.8}$	25.54
$\Delta\theta_{hi}$	---------	12.02	---------	15.89

Units: K (or °C)

Table 17 : Initial conditions after assuming values

By replacing values in Equations [4] to [10] and simplifying them, Expressions [14] and [15] emerge for lower and higher steps in the Summer and Winter Peak Periods.

$$\theta_{h_s}(t,K_2) \qquad [14]$$

$$= \begin{cases} \theta_{h1_s}(t) = 48.30 + [4.24 \times (1 + 21.96 \times K_2^2)^{0.8} - 18.92] \times e^{-\frac{t}{75}}, & Lower\ step \\ \theta_{h2_s}(t) = 48.30 + [4.24 \times (1 + 21.96 \times K_2^2)^{0.8} - 18.92] \times \cdots & , Higher\ step \\ \cdots \left(1 - e^{-\frac{t}{75}}\right) + (29.59 \times K_2^{1.3} - 12.02) \times \left(1 - 2 \times e^{-\frac{t}{14}} + e^{-\frac{t}{75}}\right) & \end{cases}$$

$$\theta_{h_w}(t, K_2) \quad [15]$$

$$= \begin{cases} \theta_{h1_w}(t) = 49.56 + [4.24 \times (1 + 21.96 \times K_2^2)^{0.8} - 25.54] \times e^{-\frac{t}{75}}, & Lower\ step \\ \theta_{h2_w}(t) = 49.56 + [4.24 \times (1 + 21.96 \times K_2^2)^{0.8} - 25.54] \times \cdots & , \quad Higher\ step \\ \cdots \left(1 - e^{-\frac{t}{75}}\right) + (29.59 \times K_2^{1.3} - 15.89) \times \left(1 - 2 \times e^{-\frac{t}{14}} + e^{-\frac{t}{75}}\right) & \end{cases}$$

The integration limits will be the following, according to the Peak Period:

	t_1	t_2
Summer Peak Period	540	900
Winter Peak Period	510	930

Units: min

Table 18 : Integration limits

By solving Equation [13] for the Summer and Winter Peak Periods, the load factors for the higher steps can be found for each of these Periods. The results were obtained with Texas Instruments Nspire CX CAS Student Software using the solve function and applying K_2 as dependent variable. Table 19 presents the cyclic overload factors and ratings of the power transformer.

	Cyclic overload ratings / factors	Fixed conditions		
		K_1 [p.u.]	t_1/t_2	θ_a [°C]
Summer Peak Period	93.12MVA / 103.47%	0.5	9/15	17.36
Winter Peak Period	99.70MVA / 110.77%	0.62	8.5/15.5	8.13

Table 19 : Load factors for the higher steps and corresponding cyclic overload factors

From the results above the Summer Peak Period is the more restrictive in terms of overloading. However, when this result is compared to Figure 5, it is possible to see that even in the day of the highest maximum demand on the Summer Peak Period, the demand is below the cyclic overload rating.

On the other hand, the Winter Peak Period presents a higher cyclic overload rating, but when is compared with Figure 6, it can be seen that this value is overtaken by demand, which means in this case as demand values are not excessively high that the transformer is ageing faster than it should be.

Verification of limits

The compliance with the limits in the Standard will be checked at t_2, when the most extreme thermal conditions of operation of the transformer are reached.

Table 20 presents the variables to comply at t_2, based on the limits defined in Table 15.

Variables to comply at t_2	Peak Periods	
	Summer	Winter
Current (or load factor, K) (p.u.)	1.0347	1.1077
Winding hot-spot temperature, θ_h, and metallic parts in contact with cellulosic insulation material (°C)	103.10	102.79
Top-oil temperature, θ_o (°C)	84.19	84.88

Table 20 : Values of variables to comply at t_2

Comparing Table 20 with the limits, it can be seen that all variables comply with the limits.

Estimation of the cyclic overload ratings with the change of the BSPMD

For this analysis the following assumptions and considerations will apply:

- Demand growth will follow the yearly growth of the BSPMD in Table 1, and will be homogenous in a 24h demand profile, which means that K_1 will have the same growth of the BSPMD from year-to-year.
- It is considered that year 2021 will have $K_1 = 0.62 p.u.$ and therefore $K_2 = 1.11 p.u.$.
- Only the Winter Peak Period will be assessed as it is the one when the BSPMD occurs and the headroom for overloading the transformer is more restrict.
- Ambient temperature and the time relation between lower and higher steps will remain constant, as no significant change is expected in the type and volume of consumers connected to Dungannon Main. So $\theta_a = 8.13$°C and $t_1/t_2 = 8.5/15.5$.

Based on the above assumptions and considerations, and using the same methodology to determine the cyclic overload rating and factor, Table 21 presents an estimate of the cyclic overload factors and ratings during the Winter Peak Period between 2021 and 2031.

Year	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
BSPMD [MVA]	101.39	101.47	101.69	102.09	102.69	103.33	104.4	104.95	105.88	107.03	107.99
Yearly growth (BSPMD) [%]	------	0.08	0.22	0.39	0.59	0.62	1.04	0.53	0.89	1.09	0.90
K_1 [p.u.]	0.6224	0.6229	0.6243	0.6267	0.6304	0.6344	0.6409	0.6443	0.6500	0.6571	0.6630
K_2 [p.u.]	1.1077	1.1077	1.1077	1.1077	1.1076	1.1076	1.1075	1.1075	1.1074	1.1073	1.1073
Cyclic overload rating [MVA]	99.70	99.69	99.69	99.69	99.69	99.68	99.68	99.67	99.67	99.66	99.65

Table 21 : Estimate of the cyclic overload factors and ratings during the Winter Peak Period

It is possible to understand that the cyclic overload rating slightly decreases during this period. However, this will not decrease significantly the transformer's overload capacity for this scenario. These values from the cyclic overload factors and ratings during the Winter Peak Period will be used on the security of supply assessment.