Secondary Network Asset Temperature Behaviour Report

A description of analysis carried out within Phase 1 of the Celsius project

Report for Electricity North West

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Executive Summary

This report details the results of Phase 1 of the Celsius project. Celsius is an innovation project funded by Ofgem's Network Innovation Competition (NIC), led by Electricity North West (ENW) with Ricardo Energy & Environment as their technical consultant.

The aim of Celsius is to increase the capacity of distribution substations, specifically the thermal capacity of transformers and cables, by investigating the behaviour of the temperature of the assets and release additional capacity through improved thermal ratings and asset cooling technologies. This will support the uptake of low carbon technologies and reduce the need for network reinforcement. The project includes two phases; Phase 1: Monitoring Trial and Phase 2: Cooling technology trial. This paper focuses on Phase 1, the monitoring trials.

Phase 1 develops a detailed understanding of the operating temperature of assets with the aim of estimating the impact of a range of asset environment factors in asset rating, which is limited by the operating temperature. The report contains three studies:

- **Transformer Hotspot Estimation Study** –a method was developed to estimate transformer Hotspot temperature; the warmest point within the transformer, which is a vital input to later analysis stages but cannot be practically measured directly.
- **Daily Thermal Ratings Study** – In order to compare the thermal behaviour of the wide variety of sites and environmental factors, a daily thermal rating was calculated for each site. This was used as an input into the Temperature Factors Study.
- **Temperature Factors Study** – A significant number of asset environment and loading factors were assessed to understand their impact on the thermal rating of the transformer. This detailed analysis investigated the relative influence and interaction between factors, as well as their impact on the rating.

The first study, the transformer hotspot temperature study, developed a model that estimated maximum operating temperature (hotspot) from accessible information such as transformer characteristics and temperatures that can be easily monitored. The result of this study was a transformer hotspot equation depending on transformer type (three specifications of Transformer are considered in the study) in the following form:

T1 (older transformers): $T_{HS} = (1.97 * S_T) - (0.81 * A_T) - 9.25$

ESI 35-1 UNIT (newer, unit transformers): $T_{HS} = (1.97 * S_T) - (0.81 * A_T) - 1.99$

ESI 35-1 (newer transformers): $T_{HS} = (1.97 * S_T) - (0.81 * A_T) - 7.11$

Where,

T_{HS} is the hotspot temperature in °C

S_T is the surface temperature at the top of the tank in °C shifted backwards in time to compensate for time lag due to thermal mass. The appropriate time lag can be calculated for each site.

A_T is the ambient temperature of the substation in °C, measured at least 2m high.

Validation of this equation included comparison of measured and calculated hotspot temperature at a site with monitoring embedded within the transformer. This validation showed an error margin between -0.8 °C and 4.97 °C, which is within the success criteria agreed with ENW. This model was used to calculate the estimated hotspot temperature of all Celsius trial sites.

Within the analysis, it was noted that individual sites on individual days showed particularly high or low daily rating results. It was concluded that this is due to unusual external circumstances, such as particular weather conditions or doors being opened. This highlights the need to take into account data across multiple days, over a sustained period of time, to gain a balanced view of the rating. A single day of data may produce misleading results.

The second study, the daily rating study, involved estimating a rating for each Celsius transformer for each day. This was done by comparing the load of each transformer with the estimated hotspot

temperature calculated in the hotspot study and considering the maximum allowable operating hotspot temperature. The Celsius data was filtered to include only the most useful data, such as only including sites on days when they are heavily loaded. The results of this study were vital to the final study.

Finally, the third study, the temperature factors study, involved building a model to estimate the daily rating from nominal rating, site and transformer characteristics and monitoring data. This estimated rating, based on the most applicable and influential temperature factors, is called the Celsius Rating. Very accurate models were achieved, producing correlation coefficients of 94% (where coefficients greater than 75% are considered to be strong correlation, and the maximum is 100%). The most influential factors included:

- **Nominal rating** of the transformer
- **Harmonics** indicated by the Total Harmonic Distortion of each phase current
- **Time of day of the peak load**
- **Site layout type** such as unit transformer, separate units, two transformers
- **Weather temperature**
- **Building type** such as brick, glass reinforced plastic, and outdoor

$$R_{Cel} = C_{NR}R_{Nom} + F_{Season} + F_{Building\ Type} + F_{Spec} + F_{Layout} + \mathrm{C}$$

Where,

R_{Cel} is the Celsius rating in kVA
C_{NR} is the nominal rating coefficient
R_{Nom} is the nominal rating in kVA
F_{Season} is a number that depends on the season of the year
$F_{Building\ Type}$ is a number that depends on the building type
F_{Spec} is a number that depends on the transformer specification
F_{Layout} is a number that depends on the layout type
C is a constant

It was noted that many of these factors relied on real-time data, such as weather data and harmonics. This study was aiming to develop a rating method that does not require real time data, so these factors were removed from the model. Upon removal of real time temperature factors, the correlation coefficient reduced by 10%. Additionally, the correlation coefficient is very high taking into account only nominal rating, and the remaining temperature factors produce no significant improvement on the correlation over this. This showed that there is the opportunity to form a simplified rating equation including only nominal rating:

$$R_{Cel\ Simplified} = 1.1R_{Nom} + 112 \ \ (kVA)$$

Where R_{Nom} is the nominal rating of the transformer.

The Celsius and Simplified Celsius Ratings can be used to give an indication of the likely rating for a site with set characteristics. However, the calculated Daily Ratings for a given site may range significantly from this result. This highlights that the Celsius and Simplified Celsius Rating should not be used as a basis for planning decisions in individual cases, and the daily rating should always be calculated.

There are some limitations to the analysis reported in this document, including:

- **Limitations to the sites included in the Transformer Hotspot Study** – The sites for this study did not include outdoor or Glass Reinforced Plastic sites, and there were limited examples of heavily loaded sites. Parts of the study were based on only three sites with direct hotspot measurement. **The result of this is that the hotspot calculation should be used as an indicative estimate only, and appropriate margins of safety used. The findings are rigorous enough for use in the temperature factors analysis as they meet the success criteria for the majority of the time.**
- **Data volumes are reduced by filters for loading and quality** – The sites used in the temperature factors study were filtered for heavy loading and data quality, which together meant that only 12% of the total data collected was used. **The result of this filtration includes 20,000**

days of data across approximately 200 sites, including a representative mixture of site types. This is considered a large enough data sample to develop rigorous results.

The next steps are to develop a temperature rating tool that will make all findings of this deliverable accessible to a user within a DNO. The tool would take information about the transformer and the site to provide a more informed transformer rating. Further work within the Celsius project, including the investigation into cooling technologies in phase 2, will be incorporated in the tool in later tasks. As limitations are resolved, such as increase in data from highly loaded transformers, the analysis reported here may be updated as agreed with ENW.

Contents

1. Introduction

The Celsius project was awarded funding under Ofgem's 2016 Network Innovation Competition (NIC). It is being led by Electricity North West (ENW). Ricardo Energy & Environment are the technical consultant partners on the project.

1.1 Celsius project Context

The aim of Celsius is to increase the capacity of distribution substations, specifically the thermal capacity of transformers and cables, by investigating the behaviour of the temperature of the assets, and release additional capacity through improved thermal ratings and substation or asset cooling technologies. This will support the uptake of low carbon technologies and reduce the need for network reinforcement. The project includes two phases:

- **Phase 1: Monitoring Trial (520 substations)** – Develops a detailed understanding of the operating temperature of assets with the aim of estimating the impact of a range of asset environment factors in asset rating, which is limited by the operating temperature of the transformer.
- **Phase 2: Cooling technology trial (100 substations)** – Identifies and demonstrates technologies that cool substation assets to release additional capacity.

This document reports the findings of the analysis undertaken in Phase 1.

The first phase of Celsius included 520 distribution substation sites, each of which has been fitted with at least one central communications hub and up to 30 sensors measuring transformer power and asset and ambient temperatures.

The site selection for the monitoring trial was carefully considered to include a representative mix of substation sites, considering the substation building structure, transformer rating, and transformer specification.

Celsius uses KeLVN monitoring equipment, provided by Ash Wireless, to provide substation data. Included in the suite installed in each substation is:

- **Single temperature sensors**, which measure a single asset or environment temperature.
- **Hex unit**, which can connect up to 6 sensors including current, voltage, and temperature. When voltage and current sensors are connected in the correct configuration, the Hex unit will calculate complex power from the data.
- **Internal transformer temperature monitoring**, which can also be connected through a Hex unit, and measures the temperature of the oil within a transformer.

This temperature and power monitoring equipment communicates half hourly readings (Temperature readings are instantaneous every half hour, while power readings are the root mean square over a 200ms averaging period) to a central Hub installed within the substation. Data is transmitted from the Hubs, once per day over the mobile network – the data is sent in four groups, each containing 6 hours' worth of data for that substation. The Hub can receive commands for a short period once a day when it connects to the back end.

The KeLVN monitoring equipment was provided by Ash Wireless and is described in more detail in a series of separate documents.

A mobile application was developed to support the installation of the equipment and recording of key installation and site data. A data management system was developed to receive data remotely from the monitoring equipment, and process, store, and provide access to it. Raw data is analysed and checked for validity and processed. This includes rounding the timestamps to the nearest half-hour in order to support validation. After processing, the data is stored. Importantly, both raw and processed data are retained for diagnostic and troubleshooting purposes. The installation app and data management system were both developed by Ricardo Energy & Environment.

In addition to the data available from the KeLVN equipment, Electricity North West have installed a number of transformers which have integrated fibre optic temperature monitoring throughout, including direct monitoring of the transformer hotspot. This data is stored through an ihost system separately to the Celsius data management system.

Weather data is also collected from freely available data sources.

1.2 Monitoring Trial Analysis: This Document

This report describes the analysis and results for Phase 1 of the project, focusing on transformers only. As agreed with ENW, the project programme will consider cables later in 2018. Phase 1 is split into 3 stages which are summarised in the flowchart below.

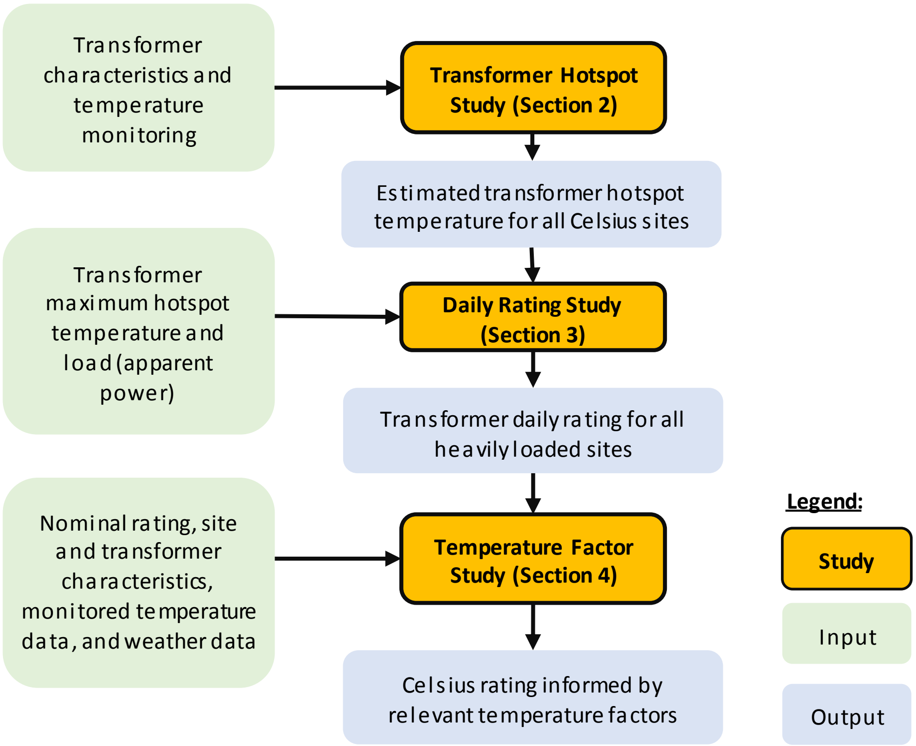

Figure 1: Flowchart representing the main stages of the analysis with the intention of developing a model that estimates a more improved thermal rating for the LV transformers at all ENW sites

The first study, the Transformer Hotspot Temperature Study, aims to develop a model that estimates maximum operating temperature (hotspot) from easily accessible information such as transformer characteristics and temperatures that can be easily monitored. This model can then be used to calculate the estimated hotspot temperature of all Celsius trial sites, which is a vital input into the following studies. The methodology and results for this study is described in section 2.

The second study is the Daily Rating Study. The aim of this study is to calculate the daily rating, which is defined as the maximum capacity in kVA that the transformer can operate at per day for a specific site. This is calculated by comparing the load of each transformer with the estimated hotspot temperature calculated in the Transformer Hotspot Study and considering the maximum allowable operating hotspot temperature. The Celsius data is filtered to include only the relevant data, such as only including sites on days when they are heavily loaded. This study is discussed in section 3.

Finally, the third study, the Temperature Factors Study, involves building a model that can estimate the daily rating from nominal rating, site and transformer characteristics and monitoring data. This estimated rating, based on the most applicable and influential temperature factors, is called the Celsius Rating. This is described in section 4.

The expected output of the monitoring trial analysis is a detailed understanding of the thermal behaviour of substation assets (in particular LV cables and transformers) under different asset environment and loading conditions. The aim is to develop an approach to estimate a more informed rating for the asset, which can then be used to inform operational and investment decisions. These ratings are estimated either using monitoring data, or through a combination of environment or loading factors that have been found to impact the operating temperature of the equipment.

It was necessary to use a statistical tool to develop statistical models due to the volumes of data and the complexity of the analysis needed. The approach was taken to use a statistical tool called Rstudio to derive the best correlation coefficient between multiple variables. The correlation coefficient R^2, which has a value between 0 and 1, indicates how good a model is for predicting the desired output term. As an indicator, an R^2 of 0.75 or 75% or above is considered to be the criteria for strong correlation.

Due to the thermal mass of the transformer, there is a time delay between the temperature peak at the hotspot and the internal oil temperature to react. The calculation of this time lag is not an important output of the Celsius analysis as the focus is on the shape and magnitude of the temperature of the hotspot temperature. However, it needs to be considered in order to build the model and validate against measured data. For all analysis steps, the time delay was calculated by shifting the data to bring the temperature peaks in line with each other before the start of the investigation.

An existing key method to produce similar results is the Rated Use of Life method, where the loading of a transformer over its lifetime is used to understand how quickly it is aging, and therefore its remaining lifetime. This method is not proposed here as it relies on significant historical data which is not available across the portfolio of GB distribution substations. Additionally, the aim of the Celsius approach is to develop generic understanding that can be applied without the need for load monitoring until the loading at the site nears the rated limits.

This document reflects the project findings up to August 2018. A previous report was delivered in April 2018, and this report supersedes that previous report. These findings will be built on and developed over the rest of the project, and therefore may evolve over time.

2. Transformer Hotspot Estimation

The transformer '*hotspot'* is the location of the hottest part of an operational transformer, and is located within the transformer itself, towards the centre. It is this temperature that is of interest within the Celsius analysis, but it is not practical to have retrofitted monitoring installed to measure the temperature directly. The aim of the Transformer Hotspot Estimation was to develop a method to estimate the transformer hotspot temperature from surface temperature measurements and other easily accessible information, for all ground mounted transformers within the Celsius trials. This calculated hotspot temperature was then used within the temperature factors analysis to analyse the impact of asset environment and loading factors on operating temperature.

A number of aims were taken into account to determine the most effective solution:

- The success criteria for this work has been determined by Ricardo Energy & Environment and agreed with Electricity North West. A successful model will predict hotspot temperature data to within ±5°C of the measured hotspot temperature, which has been directly measured at some sites.
- The model needs to be based on data and information that is easily collected and accessible from the outside of the transformer (meaning that it cannot rely on any internal measurements).
- The model should not rely on measurement of transformer loading. It is recognised that transformer loading is a driving factor of the operating temperature of the transformer. However, the focus of Celsius is to investigate the other factors that drive temperature, and so aimed to develop a method of estimating temperature more akin to direct measurement, rather than calculating from load.

This section describes the methodology, analysis and results for this study. There are several key limitations to the transformer hotspot study and its results, which are described in Section 2.4.

2.1 Published methods of Hotspot Calculation

There are published methods for predicting the hotspot temperature which have been investigated during the hotspot study. A key example is IS 2026 (Part 7): 2009; IEC 60076-7: 2005 Loading Guide for Oil-Immersed Power Transformers [1]. The methodology to estimate the hotspot temperature is based on three inputs which are transformer loading, ambient temperature and the features of the transformer.

This method is a useful point of information but was discounted as the basis for the core methodology to develop the hotspot model. As mentioned previously, the Celsius generic model should not rely on measurement of the transformer loading. The project aims to investigate how other factors influence the operating temperature from which a model can be developed based on direct measurement. The published standard also assumes that the user has information relating to the transformers characteristics available. Ricardo Energy & Environment needs to be able to apply the model across the portfolio of transformers, for many of which the required data is not available. These are the two main limitations which prevented Ricardo Energy & Environment from using the published standard going forward. This means that a generic model had to be developed with the data and information that was available at the time.

A comparison was made between the published hotspot temperature approach and the Celsius hotspot temperature approach to test the accuracy of the model. This is discussed in section 2.5.

2.2 Hotspot Methodology

The configuration of sensors across the Celsius sites varies; all Celsius sites have at least single-phase power monitoring and a range of asset surface and ambient air temperature monitoring, but some sites are fitted with additional sensors to provide specific insight for the Transformer Hotspot Study.

These include 17 sites that have three phase power monitoring, increased transformer surface temperature monitoring, and additional sensors inside the body of the transformer measuring the temperature of the transformer oil at the top and bottom of the tank. The selection of these transformers aimed to include a representative sample of the GB ground mounted LV transformer portfolio, including a range of ages, specifications, and sizes. Due to safety and security reasons, all the transformers selected for internal measurement were indoor.

Of these 17 sites, 5 were 'smart transformers' which have integrated fibre optic temperature monitoring throughout, including direct monitoring of the transformer hotspot. These substations were of special importance, as they provided access to measured hotspot temperatures alongside the oil, surface and ambient temperature sensors described above.

The approach to this study was as follows:

- **Step 1: Link between hotspot temperature and internal oil temperatures** – Step 1 involved investigating the relationship between the measured hotspot and internal oil temperatures of the smart transformers. Only those that were loaded above 25% average utilisation over the 6 months of the study were considered in this analysis. Other data such as ambient temperature, transformer specification, rating, and mass was included in the investigation to determine whether this improved the performance of the model. A generic model was developed for one of the smart transformers, and then validated with two additional transformers.
- **Step 2: Link between internal oil temperatures and external surface temperatures** – Step 2 involved using the internal oil measurements from the 17 transformer sites to investigate the relationship between the internal oil temperatures and their corresponding external surface temperatures, installed as close as possible to the internal sensor positions. As in Step 1, other information was considered for inclusion in this method. A generic model was developed using 75% of the available data for each site, and the other 25% was used for validation.
- **Step 3: Hotspot temperature calculated from external surface temperature** – The results from step 1 and 2 were combined to develop an expression which can estimate the hotspot temperature from externally accessible measurements and transformer characteristics.
- **Step 4: Determine how measurement variations impact this methodology** – The installation of surface temperature equipment is not consistent across all Celsius sites. Consideration was made to the appropriateness of applying the hotspot methodology across the Celsius sites.

2.3 Step 1: Link between hotspot temperature and internal oil temperatures

The Celsius trial includes 5 smart transformers, with direct measurement of the hotspot temperature. However, it was not possible to use all of the smart transformers, as the peak loading that some of the transformers experienced was not high enough. It was necessary to focus on heavily loaded transformers to model the thermal behaviour of transformers as they approach their rated loading.

A peak loading value of 70% was selected as the threshold to be included in the analysis. However, the loading of the smart transformers was generally low. With this in mind, ENW undertook to increase the loading of the smart transformers where possible. The average and maximum loading of the smart transformers from July 2017 to March 2018 are indicated in the Table 1 below.

Transformer Site	Average Utilisation %	Maximum Utilisation %
Helsby Way	16%	60%
Clarendon Rd T2	19%	73%
Jessel CL	24%	51%
Jenny LN	26%	60%
Clarendon Rd T1	32%	72%
Kincardine Rd	46%	89%

Table 1: Average and maximum loading of the smart transformers from July 2017 to March 2018

Only Kincardine Rd regularly has adequate loading to be considered for this study, and the Clarendon Road transformers have occasionally heavily loaded data. It was decided that Kincardine Rd would be used to build the generic model that calculates hotspot from the internal temperature at the top of the tank while both Clarendon Rd T1 and T2 was used to validate this model. ENW have worked on increasing loading at Clarendon Road to enable this validation. Between 10/06/2018 and 10/07/2018, loading of T1 has been increased to an average of 52%, and a maximum of 82%, and is regularly at or close to 70% loaded. ENW then switched over to T2 and between 26/06/2018 to 13/08/2018, loading at T2 increased to an average of 51% and a maximum of 79%.

Regression analysis was run in the statistical tool Rstudio to investigate the most appropriate model to estimate the hotspot temperature of an operational transformer. This regression was based on data from Kincardine Road, between July 2017 and March 2018. The variables included in the regression study were:

- the internal oil temperature at the top oil level
- the internal oil temperature at the bottom of the transformer tank
- the ambient temperature high in the room
- the ambient temperature near the floor

The variable that was most closely related to the measured hotspot temperature was found to be the internal oil temperature at the top oil level. The expression for this relationship was as follows:

$$T_{HS} = (1.169 * T_I) - 5.069$$

Where,

T_{HS} is the hotspot temperature in °C

T_I is the internal temperature at the top of the tank in °C

The residuals are the difference between the calculated and measured hotspot, and are therefore an indication of the error in the calculated verses the measured values. These were plotted against hotspot temperature (Figure 2), and against date (Figure 3) at Kincardine Rd from July 2017 to March 2018.

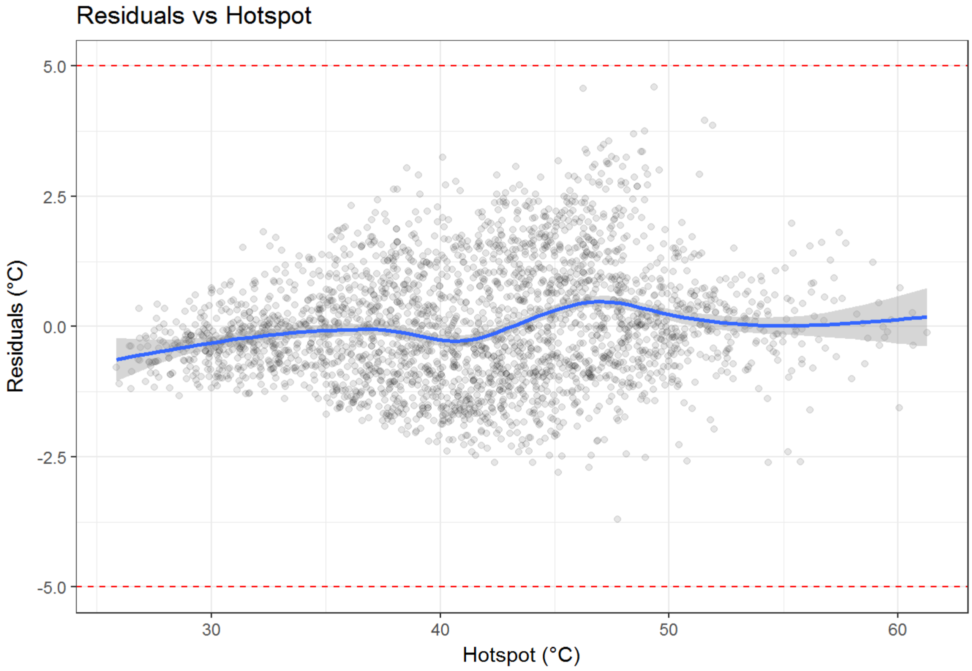

Figure 2: Residual between the calculated and measured hotspot using a calculation based on internal temperature, plotted against measured hotspot at Kincardine Rd from July 2017 to March 2018

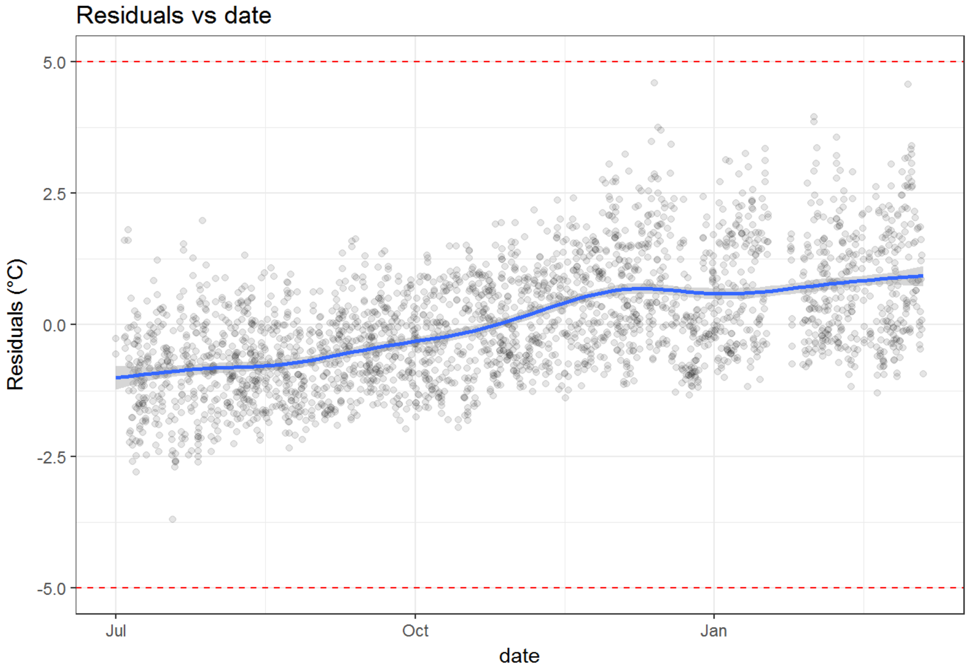

Figure 3: Residual between the calculated and measured hotspot using a calculation based on internal temperature, plotted against measurement time at Kincardine Rd from July 2017 to March 2018

As can be seen from Figure 2 and 3, the residuals are between -5°C and +5°C, indicating that the model is never more than 5°C from the measured result. However, the aim is for the complete methodology to be within 5ºC of the measured values, and therefore there is a need to improve the accuracy of this step.

Figure 2 indicates that there is little or no overall trend impacting this residual relating to hotspot data, as the average line shown in blue lies largely along the 0 axis. However, Figure 3 shows a trend in residuals over time, where they are lower in the summer months, and higher in winter. For this reason, a second variable of ambient temperature was selected for inclusion into the model.

The results of a regression analysis that predicts the hotspot temperature based on the internal top oil temperature and ambient temperature at high levels show that the correlation coefficient increased from 0.97 to 0.99, indicating that a more accurate model for calculated hotspot temperature was achieved. The new equation was as follows:

$$T_{HS} = (1.397 * T_I) - (0.272 * A_T) - 9.35$$

Where,

T_{HS} is the hotspot temperature in °C

T_I is the internal temperature at the top of the tank in °C

A_T is the ambient temperature at high level in °C

The comparison between calculated and measured hotspot temperatures are shown in the residual plots in Figure 4.

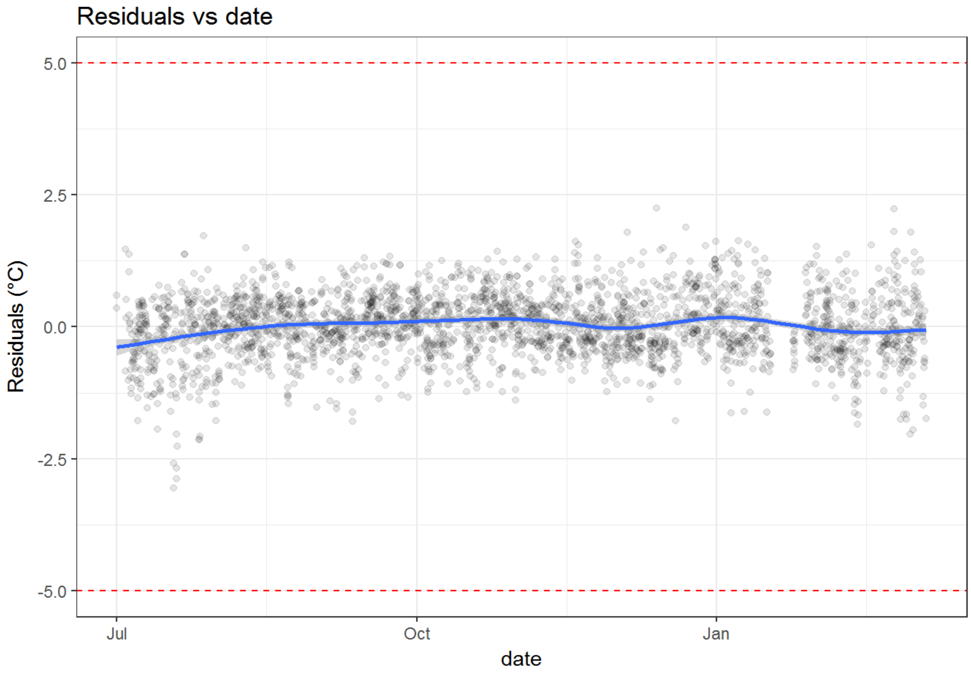

Figure 4: Residual between the calculated and measured hotspot using a calculation based on surface and ambient temperature, plotted against measurement time

The results in Figure 4 show that residual between calculated and measured hotspot are significantly less than in Figure 2 and 3, and are generally between -2.5°C and +2.5°C. This means that taking ambient temperature into account has made the model better at predicating the hotspot temperature.

This model was validated with data from Clarendon Rd T1 and T2. The data used was from mid-June to early July 2018 for T1, as before this time the site was too lightly loaded to provide useful validation data. The generic model produced from Kincardine Rd was tested for this site and the results are shown in Figure 5 below. This compared the calculated generic hotspot model to measured hotspot data from ENW's database.

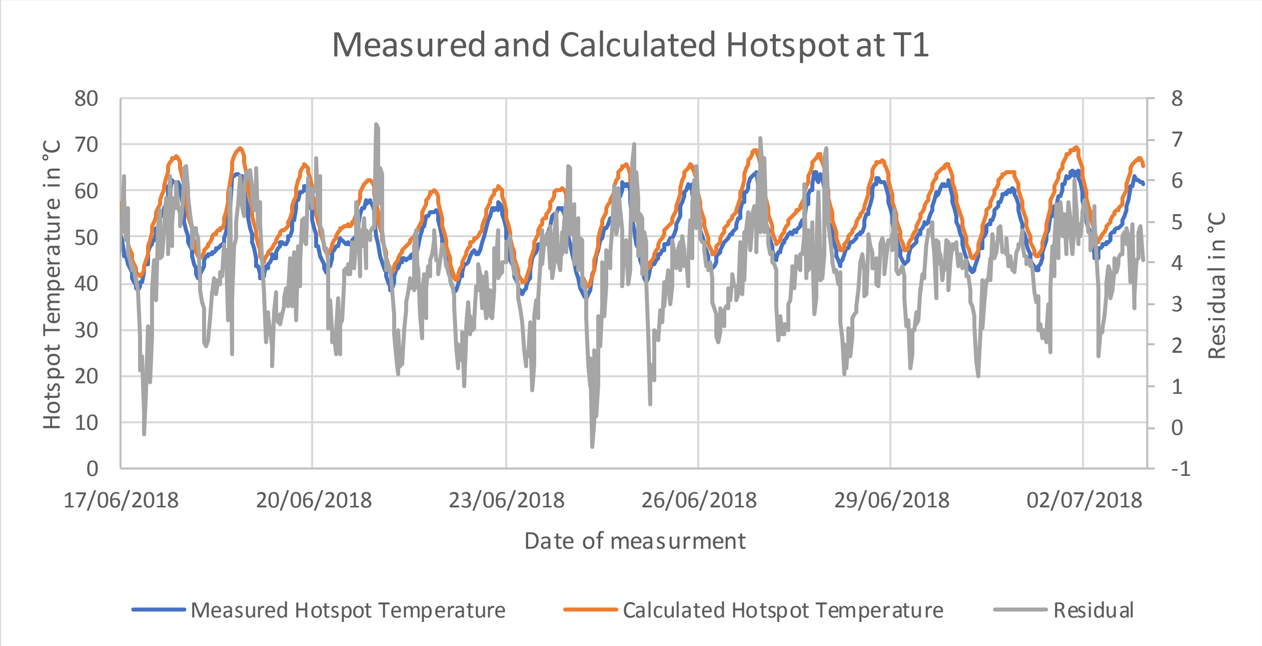

Figure 5: Validation test of hotspot prediction using data from Clarendon Rd Transformer 1

The difference between measured and calculated hotspot values shown in Figure 5 is approximately 4ºC on average. However, there are instances when the residuals exceed 5ºC. The cyclic nature of the error suggests that the transformer heats up slower, and not as much, as the model suggests.

Although time shift is not important it is recognised that this will influence the residual values and produce numbers that are higher than the true value. The data was shifted backwards by 1 hour 30 min in order to reduce the maximum residuals. However, there were still instances greater than the 5ºC success criteria. After analysing the data in more detail, it was found that 90% of the time the error margins will not exceed 5.3ºC.

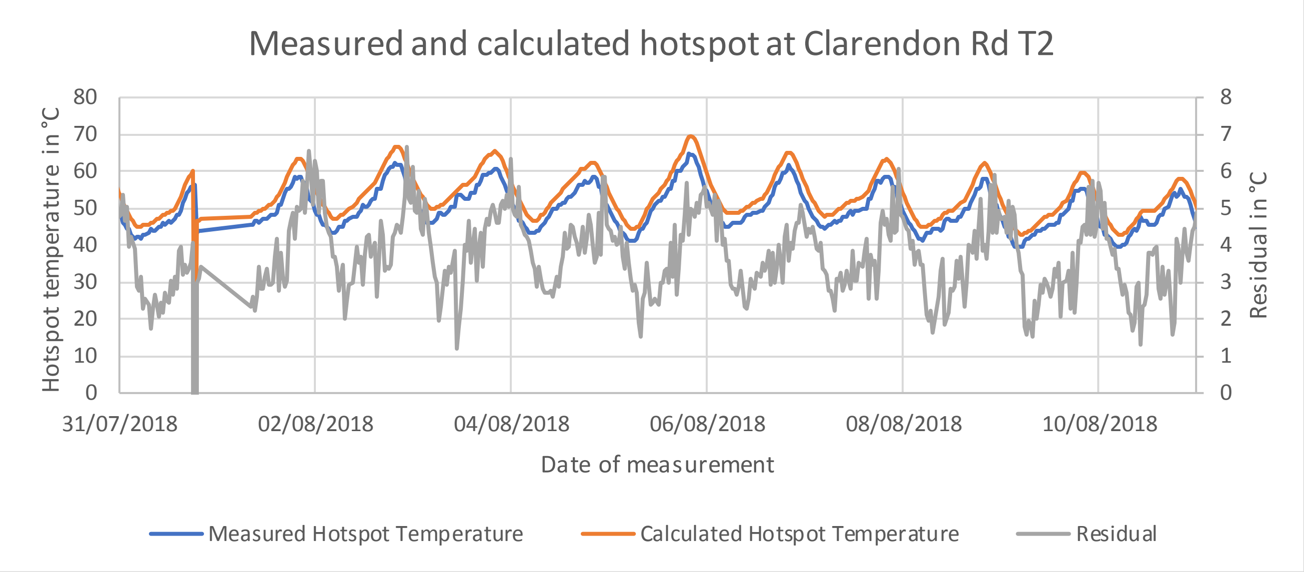

Figure 6: Validation test of hotspot prediction using data from Clarendon Rd Transformer 2

The results for T2 produced an average error between the measured and calculated hotspot which is approximately 3.68 ºC. Similarly, to T2 above, there are instances when the residuals exceed 5ºC. The time shift used for this data is 1 hour 30 min, and again inaccuracies in this will make errors appear larger than they are. After further investigation, it was found that 90% of the time the error margins will not exceed 5.16ºC.

It should be noted that the results are conservative, meaning that the model predicts a higher temperature than measured, which is the preferable position as it allows for a margin of error. The majority of the time the error is within 5ºC which suggests that a generic model that was modelled for Kincardine Rd is a valid estimator of hotspot temperature.

The major limitation for this step is the lack of a larger range of transformers with hotspot monitoring, that are adequately loaded for inclusion in the analysis. The analysis is based on a single, modern transformer, and is validated using two more transformers of the same specification. This brings into question the validity of applying this method across the varied portfolio of distribution substations, which has a wide range of transformer specifications, ages, and environments. However, as retrofitting direct hotspot monitoring into existing transformer stock is impractical, it is not possible to develop a more accurate model within the bounds of this project.

It is recommended that results of this model should be considered as an indication of hotspot temperature, rather than an accurate representation, and that appropriate safety margins are adopted.

2.4 Step 2: Link between internal top oil temperature and external surface temperatures

As described in Section 2.2, Step 2 used all 17 sites that have internal monitoring installed at their transformers to develop a model that can calculate the internal top oil temperature from known information and data that can be gained easily from the outside of the transformer.

The aim was to develop a model that can represent the range of sites, which includes transformers of different specifications and sizes, and different site characteristics. The table below shows details for the 17 sites with internal monitoring installed, including average and maximum utilisation between early July 2017 and the end of February 2018. This was the period of data that was used to build a generic model between the internal top oil temperature and external surface temperature.

Transformer Site	Transformer Specification	Rating (kVA)	Average Utilisation %	Maximum Utilisation %
ABC Ardwick	ESI 35-1	1000	39.8%	77.1%
Clarendon Rd T1	ESI 35-1	1000	31.6%	72.0%
Clarendon Rd T2	ESI 35-1	1000	19.2%	73.0%
Dudley ST	T1	750	22.9%	52.6%
Helsby Way	ESI 35-1	800	15.9%	59.7%
Jenny LN	ESI 35-1	500	25.5%	60.3%
Jessel CL	T1	500	24.4%	51.4%
Kincardine Rd	ESI 35-1	1000	45.9%	88.7%
Lancaster Ave	T1	300	30.8%	89.0%
Leicester Ave	T1	500	26.1%	54.4%
Mount ST RMU	T1	750	23.2%	51.1%
Offerton DR	T1	500	34.2%	83.0%
Shackleton CT	ESI 35-1	500	25.3%	77.0%
Victoria RD Eccles	T1	750	45.2%	85.9%
Whitefriars	T1	750	42.5%	77.5%
Windsor Rd Prestwich	T1	1000	19.8%	68.6%
Woodend LN	ESI 35-1	315	30.4%	70.3%
Wordsworth Rd	ESI 35-1 UNIT	500	44.7%	97.0%

Table 2: Internal monitoring sites, including load data

The information used in the investigation included:

- **Site Characteristics:**
  - Site latitude
  - Site longitude
  - Site layout (including number of transformers, unit substation)
  - Substation building type (for example, brick, glass reinforced plastic, outdoor fenced enclosure)
- **Transformer Characteristics:**
  - Oil mass
  - Age of the transformer
  - Transformer specification (T1, ESI 35-1 and ESI 35-1 UNIT)
  - Transformer rating
- **Measured Data from Site:**
  - Surface temperature at the top and bottom of the tank
  - Ambient temperature at high level
  - Other measured data from Celsius trial

For the transformer specification, T1 is an old transformer which was in operation as far back as the 1929. ESI 35-1 is a new transformer design which was adopted as far back as 1972 due to European standards. Finally, ESI 35-1 UNIT is a unit transformer where both the transformer, LV board and RMU are combined into one unit.

All of the characteristics were considered for use in the model. The relative influence of each variable on the internal top oil temperature was compared, and the most influential were included in the model in turn to compare the fitness of the resulting model. As in Step 1, correlation coefficient R^2 is used as a measure of the success of the model to compare the results.

Figure 7 below compares the R^2 for models containing the most influential characteristics. The figure below uses data from July 2017 to February 2018 along with site information for all internal monitoring sites listed in table 2. In this figure, the following variables are shown:

- **Surface_temp** – the temperature measured on the surface of the transformer at the top oil level which is directly adjacent to the sensor measuring the internal top oil temperature
- **Tx.Sp** – the transformer specification. Three specifications were included; T1 (older transformer), ESI 35-1 (recent transformers conforming to the European standard), and ESI 35-1 UNIT (unit transformer)
- **Amb_temp** – the ambient temperature within the substation, measured away from the transformer at a high level off the ground.
- **Bld_type** – the substation building type, which for this subset of sites includes only stone/brick, and substations that are part of a larger building.
- **Age** – this is the age of the transformer, taken from the manufacture year.

All other factors that were included were found to have an insignificant impact on the success of the model, and so are not shown. It should be noted that this analysis approach considers each variable in turn, which means that where variables are closely related, the inclusion of one variable will mean that another is disregarded as they do not add additional information to the model.

For example, the temperature on the surface of the transformer at the bottom of the tank is closely related to the top oil level surface temperature, so once the top oil surface temperature is included, there is no benefit in also including the surface temperature at the bottom of the tank. This is not to say that the surface temperature at the bottom of the tank is not related to internal oil temperature, simply that the optimal model does not include it as a variable.

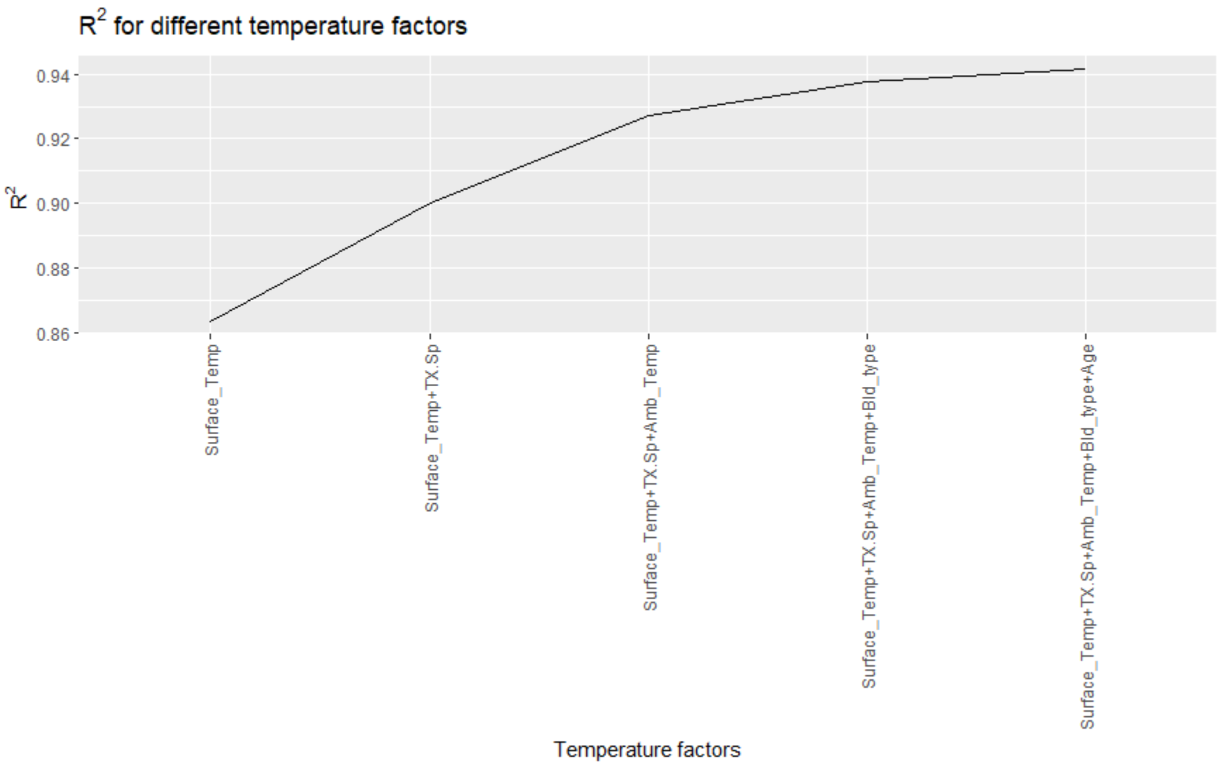

Figure 7: Correlation coefficient for models estimating internal top oil temperature from a range of temperature factors

From Figure 7, it can be seen that a model based on only surface temperature at the top oil level produces a strong model, with an R^2 of just under 0.87. Adding the transformer specification followed by ambient temperature, building type, and age improves the model and the correlation coefficient variable increases, with an R^2 of over 0.94 for a model that includes all of the factors.

There is a balance to be struck between fit of the model and its usability and complexity. The most impactful factors are surface temperature, transformer specification, and ambient temperature, which together increase the R^2 to nearly 0.93. The age of the transformer and the building type have a lesser effect on the model, together only increasing the R^2 value by another 0.01, and so they were not used to build the generic model.

The final model will predict the internal temperature at the top of the tank based on surface temperature, ambient temperature and which transformer specification category the site falls into. Note that there is only one example of the unit transformer specification, which will have an impact on the accuracy of this model.

T1: $T_I = (1.407 * S_T) - (0.385 * A_T) + 0.071$

ESI 35-1 UNIT: $T_I = (1.407 * S_T) - (0.385 * A_T) + 5.265$

ESI 35-1: $T_I = (1.407 * S_T) - (0.385 * A_T) + 1.606$

Where,

T_I is the internal temperature at the top of the tank in °C

S_T is the external surface temperature at the top of the tank in °C

A_T is the ambient temperature at the high level in °C

The three models were used to calculate the internal top oil temperature for each of the 17 sites with internal measurement, and this was compared with measured results to obtain the residuals, which represents the error in °C between the calculated and measured internal temperature.

Three plots are shown in Figure 8 below which represents the residuals against the time of the measurements for all internal monitoring sites for each transformer specification category. The red dash line represents ±5ºC error.

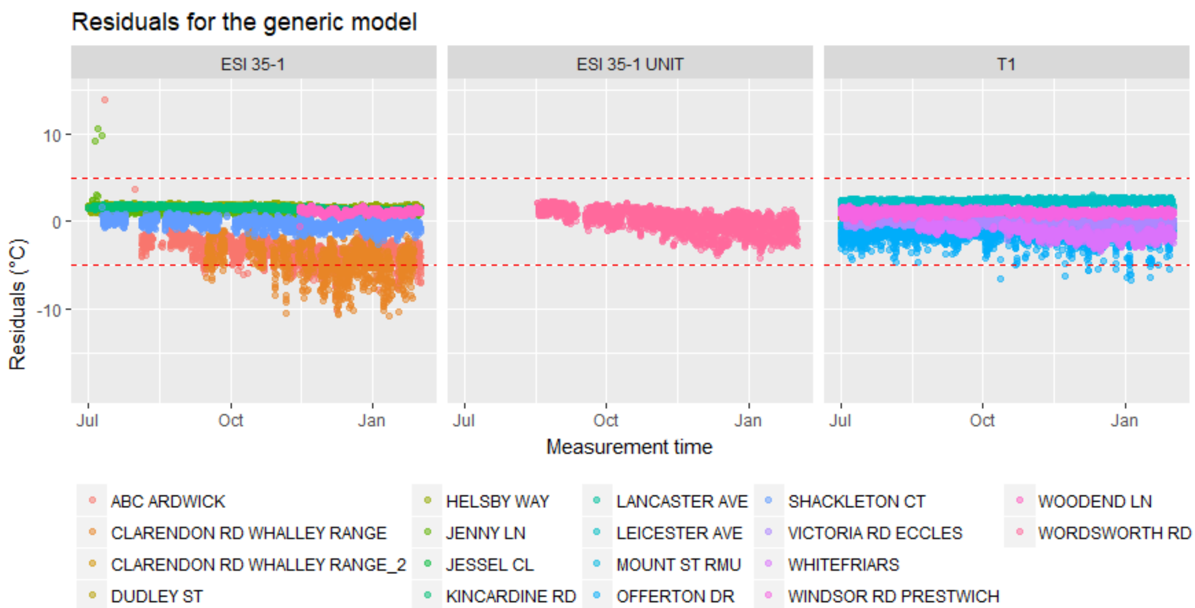

Figure 8: The error in °C between the calculated and measured internal top oil temperature for all internal monitoring sites, separated by specification category

The results in Figure 8 show that the three generic models work reasonably well across all 17 internal monitoring sites and have an error range that is within ±5ºC, with the exception of two sites in the ESI 35-1 transformer spec category; Clarendon Rd and ABC Ardwick.

A number of factors could explain these increased errors; both transformers are relatively lightly loaded within the analysis period, with transformer 2 at Clarendon Rd having an average utilisation of 19% over this period. Additionally, Clarendon Rd has two transformers within one site and the interaction between the transformers could explain why the assets are a higher temperature than expected.

After ENW increased the load on both transformers at Clarendon Rd this site was investigated further. It was discovered that the external surface temperature sensor at transformer 1 is distorted and producing inaccurate values. This means that transformer 1 cannot be investigated any further until this sensor is fixed. However, during the period of heavier loading at transformer 2, a comparison between the measured internal temperature and the calculated internal temperature was made and the results are as follows:

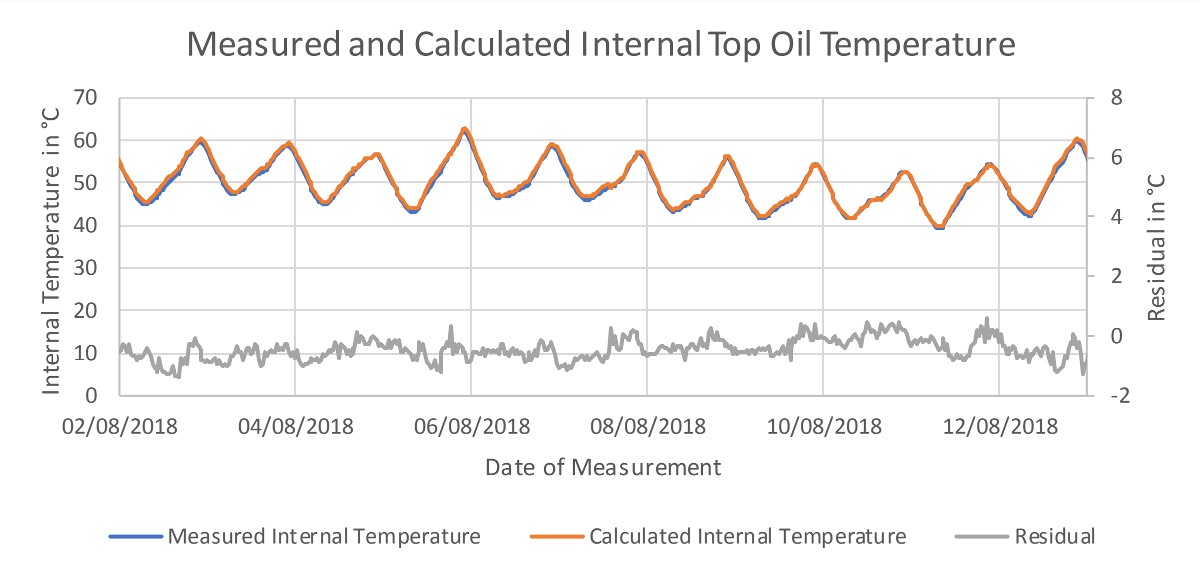

Figure 9: Measured and calculated internal top oil temperature from external surface temperature and ambient temperature over a heavier loaded time period at T2

It can be seen that increasing the loading on transformer 2 reduces the residuals to be within ±5°C. This is evidence that increasing the loading produces a more accurate estimation of the hotspot temperature, increasing the validity of the model in heavily loaded cases.

The main limitation for the results of Step 2 is the site selection, as the selection could not cover all building types and specifications. Specifically, no outdoor or Glass Reinforced Plastic (GRP) sites could be fitted with internal monitoring equipment due to reasons of safety and practicality. Therefore, the application of this method to these site types has not been validated and should be considered carefully.

The sites were also relatively lightly loaded, with limited examples of heavy loading, as illustrated in Table 2. This may have distorted the results, as the focus of this investigation should be on heavily loaded sites.

For these reasons, there are limitations to the degree to which the results can be applied across the full portfolio of sites and to explore the behaviour of very heavily loaded transformers. Again, application of this method should be used as an indication only, and appropriate safety margins should be adopted.

2.5 Step 3: Hotspot temperature calculated from external surface temperature

Using the results from section 2.3 and 2.4 a generic model can be developed which calculates the hotspot temperature from external surface temperature, ambient temperature and from which transformer specification the sites falls into. The results are as follows:

T1: $T_{HS} = (1.97 * S_T) - (0.81 * A_T) - 9.25$

ESI 35-1 UNIT: $T_{HS} = (1.97 * S_T) - (0.81 * A_T) - 1.99$

ESI 35-1: $T_{HS} = (1.97 * S_T) - (0.81 * A_T) - 7.11$

Where,

T_{HS} is the hotspot temperature in °C

S_T is the surface temperature at the top of the tank in °C shifted backwards in time to compensate for time lag due to thermal mass. The appropriate time lag can be calculated for each site

A_T is the ambient temperature at high level in °C

2.5.1 Hotspot Equation Validation

January 2018 to July 2018 was the period of data that was used to validate the model at Kincardine Rd. Using the equation above for ESI 35-1, which is the transformer specification at Kincardine Rd, the hotspot temperature was calculated. A comparison was then made between the calculated hotspot temperature and the measured hotspot data on the ihost website. Due to the errors in the models for Steps 1 and 2, the overall error margin is approximately between -0.8 °C to 4.97 °C, which is within the ±5°C success criteria. An example from late March 2018 to the early June 2018 is shown below:

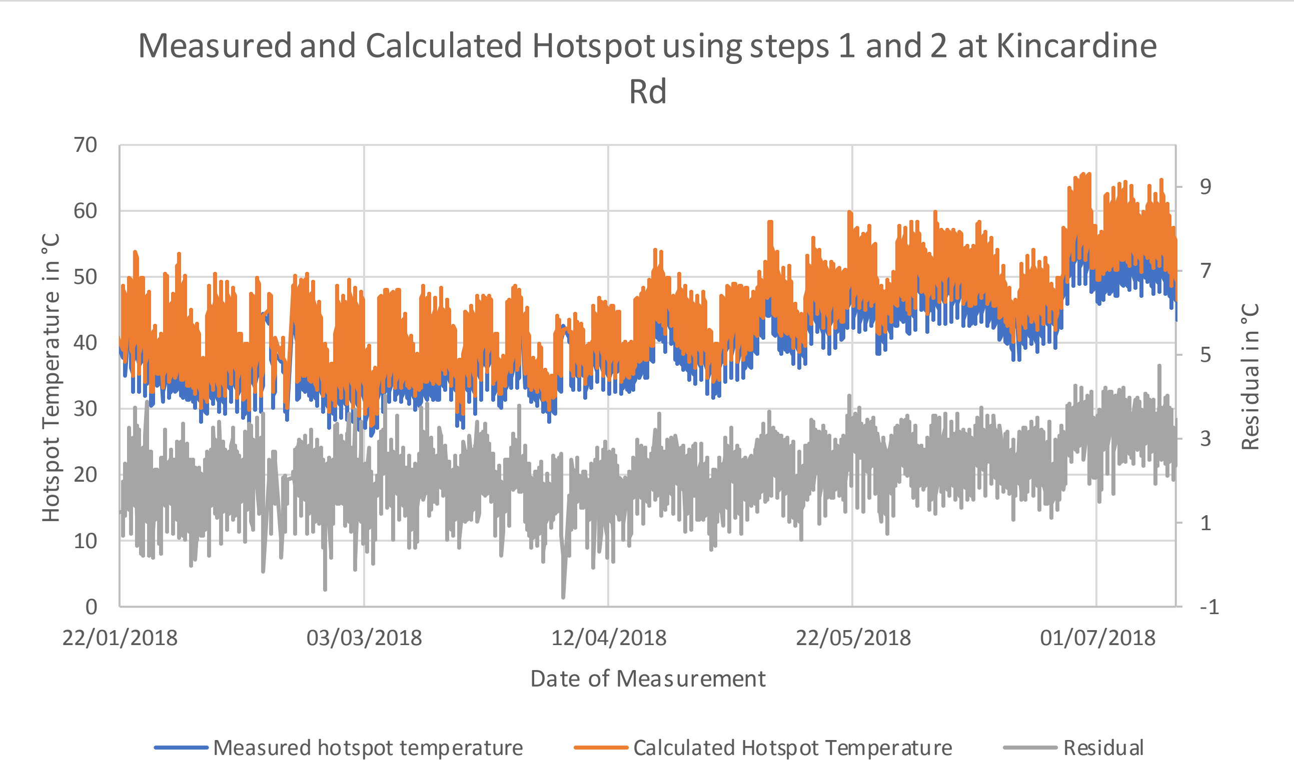

Figure 10: Comparison of the measured hotspot temperature, and the estimated hotspot using the model derived from steps 1 and 2 in the previous section

From the figure, there is a good correlation between the calculated and measured hotspot temperature and the residuals are within the success criteria.

A similar analysis was done for both transformers at Clarendon Rd.

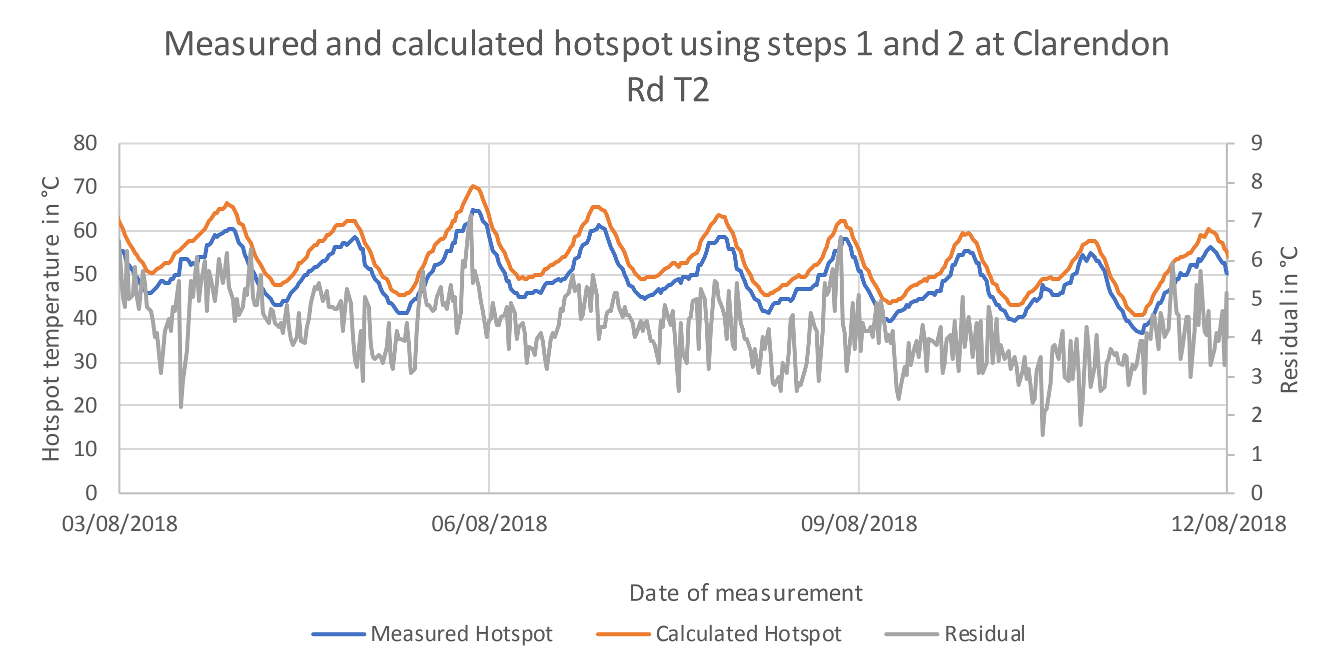

Figure 11: Measured and calculated hotspot temperature using steps 1 and 2 at Clarendon Rd T2

For the validation at T2, the average error is 4.24 °C with a maximum error exceeding 5 °C. For 90% of the time, the error did not exceed 5.6 °C.

Due to the external top oil surface temperature at transformer 1 having distortion issues, an average was calculated for the other top oil temperature sensors and the validation was carried out. Note that only three top oil temperature sensors were available during the period when transformer 1 was loaded up.

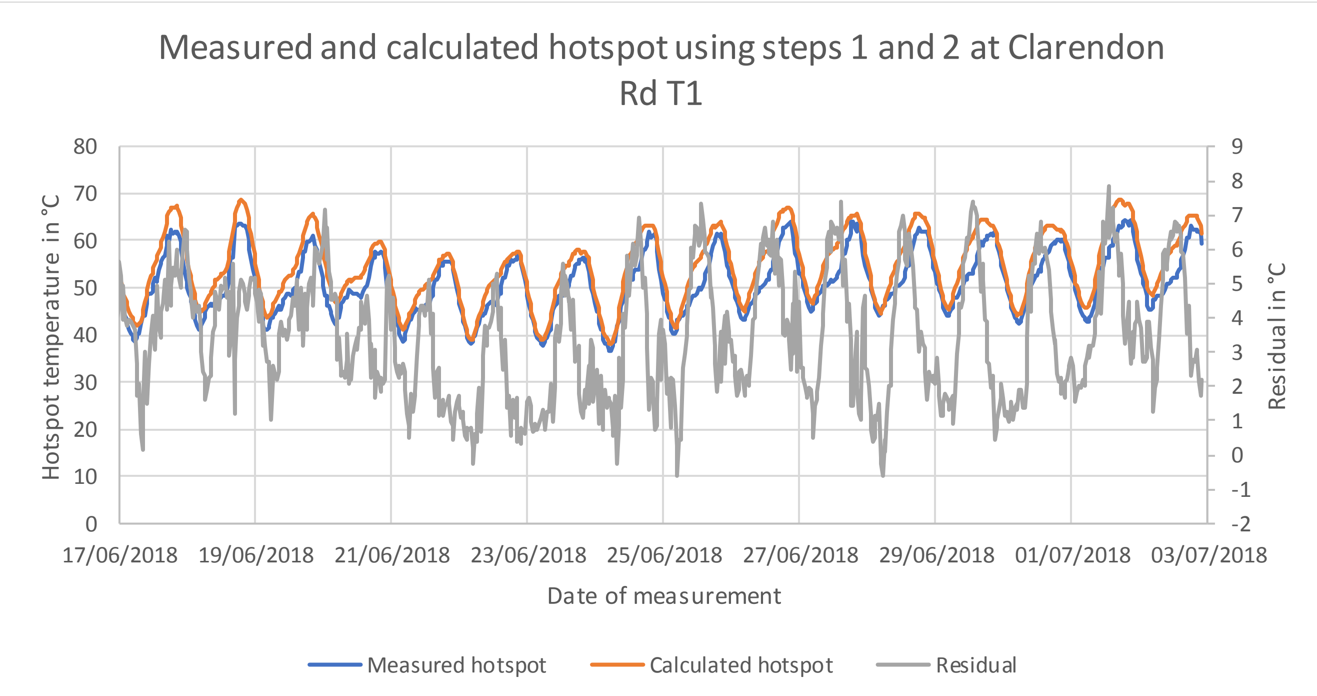

Figure 12: Measured and calculated hotspot temperature using steps 1 and 2 at Clarendon Rd T1

By using this approach for transformer 1, the average error is 3.3 °C with a maximum error exceeding 5 °C. For 90% of the time, the error did not exceed 5.95 °C.

The equation produces conservative results, as the calculated temperature is a little larger than measured. This is a preferable result, as it provides additional safety margins, rather than risking under-estimates.

2.5.2 Comparison to published methods

Published standards, which calculate maximum operating temperature using a different methodology, were considered for comparison to Ricardo Energy & Environments generic model. The standard used for this comparison was IS 2026 (Part 7): 2009, IEC 60076-7 : 2005 [1]. The hotspot approach used by the standards depended on the load of the transformer, ambient temperature and information about the transformer.

As discussed previously, these standards were not used directly within this analysis for several key reasons. These included that the standards require a significant amount of asset information as input, much of which is not known for the Celsius sites. In addition, the standard methods rely on the load as an input to the calculation, which was deemed to be inappropriate for the Celsius methodology. The information about the transformer that was required is as follows;

- K_{11} is the thermal model constant
- K_{21} is the thermal model constant
- K_{22} is the thermal model constant
- τ_0 is the oil time constant in minutes
- τ_w is the winding time constant in minutes
- × is the exponential power of total losses verses top oil (in tank) temperature rise (oil exponent)
- y is the exponential power of current verses winding temperature rise (winding exponent)
- D_t is time interval which is half the winding time constant in minutes
- R is the ratio of load losses at rated current to no load losses
- $\Delta\theta_{or}$ is the top oil temperature rise in steady state at rated losses in kelvin
- $\Delta\theta_{hr}$ is the hotspot to top oil gradient at rated current in kelvin

Table 3 below show the assumptions that were used for this analysis. These values were provided in the standards for distribution transformers.

Equation term	Assumed value
Oil exponent x	0.8
Winding exponent y	1.6
Constant K_{11}	1.0
Constant K_{21}	1.0
Constant K_{22}	2.0
Time constant τ_0	180
Top oil temperature rise $\Delta\theta_{or}$	45
Hotspot to top oil gradient $\Delta\theta_{hr}$	35
Ratio of full load losses to no load losses R	8
Winding time constant τ_w	60
Time interval D_t	30

Table 3: Distribution transformer table provided in the published standards IS 2026 (Part 7): 2009, IEC 60076-7 : 2005

From mid-June to mid-July, the utilisation and ambient temperature provided from the kelvin data for Kincardine Rd was used along with the parameters above to estimate the hotspot temperature.

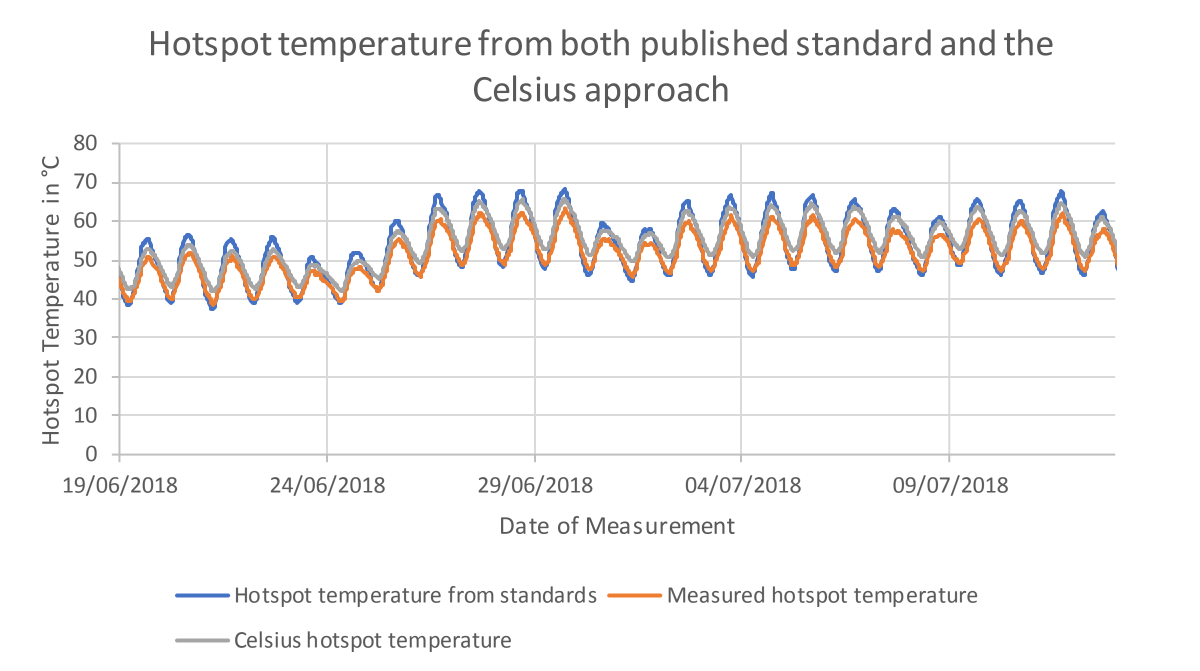

Figure 13: Hotspot temperature from both the published standard, measured data from ENW's smart transformer and the Celsius approach to estimate hotspot temperature

From the graph above, the hotspot temperature using the standards and Ricardo Energy & Environment's approach are reasonably close to each other and have approximately the same error margins with respect to the measured hotspot data at the peak load times. This is further illustrated in the table below.

	Average Error (ºC)	Maximum Error (ºC)
Error between Hotspot temperature from the published standards and measured hotspot temperature	2.53	6.71
Error between Hotspot temperature using the Celsius approach and measured hotspot temperature	2.86	4.73

Table 4: A comparison between hotspot data and the standard and Celsius approach to estimate the hotspot along with the associated error of each model

The overall error associated with using either the standard or Celsius approach to estimating hotspot temperature with respect to the measured hotspot temperature are similar. The standard approach produces an estimated hotspot temperature, which is on average, more accurate compared to the Celsius approach, however, the maximum error is greater for the published standards compared to the Celsius method. With reference to the graph, it can be seen that the Celsius calculation tends to be more accurate at the peak loading times, which is the most critical time for our analysis.

From this analysis, it can be concluded that the Celsius method has similar success in estimating measured hotspot to the published standards, which is further validation for the success of the method.

2.6 Step 4: Determine how measurement variations impact this methodology

The methodology must be applied to Celsius sites to provide the hotspot data, which is an integral part of the next stage of the temperature factors analysis. Therefore, thought has been given as to how this can be achieved.

As described in Section 2.5, the model requires the following key information:

- Transformer surface temperature at the top oil level in °C
- Ambient temperature at high level in °C
- Transformer specification

At each Celsius site, this information is being collected and reported. The aim has been to standardise the collection of data to ensure it is comparable, however the practicalities of the installation process and the need to define that process before the learning from the trials are developed mean that this is not always possible. The sections below explore this further.

2.6.1 Transformer surface temperature at the top oil level

It is recognised that the transformer surface temperature is the most critical factor in the hotspot model.

Due to the practicalities of installation, positioning of the surface temperature monitoring on the transformer surface varies considerably across the Celsius sites. While the sensors used to develop Step 2 of the hotspot model were in a consistent location on the surface of the transformer, the same consistency was not applied across the whole Celsius trial. Therefore, an investigation was performed to understand the impact of this variation, based on additional surface temperature monitoring installed at the 17 sites used for the Step 2 analysis.

The sensor positions on the surface of the transformer at the top oil level at each of these 17 sites include one on each of the four surfaces, and an additional sensor adjacent to the internal oil sensor, the latter of which was used for the Step 2 analysis.

Figure 14 shows a diagram of the transformer of Kincardine Road, and the position of the five top oil level surface temperatures, where the dark blue dot indicates the position of the sensor adjacent to the internal oil sensor, and the other coloured dots show approximate position of the other four sensors. Note that as positioning is restricted by the features of the transformer itself, this positioning is not consistent between the 17 sites. However, there is always one sensor per face in addition to the one that is adjacent to the internal sensors.

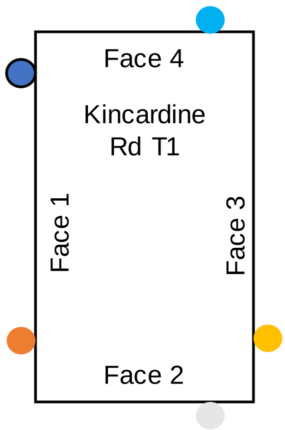

Figure 14: Position of the 5 top oil surface temperatures on the transformer at Kincardine Rd

A plot of all temperature sensors at Kincardine Rd is shown in Figure 15 below. The five temperatures are closely related, but there is a small difference between them.

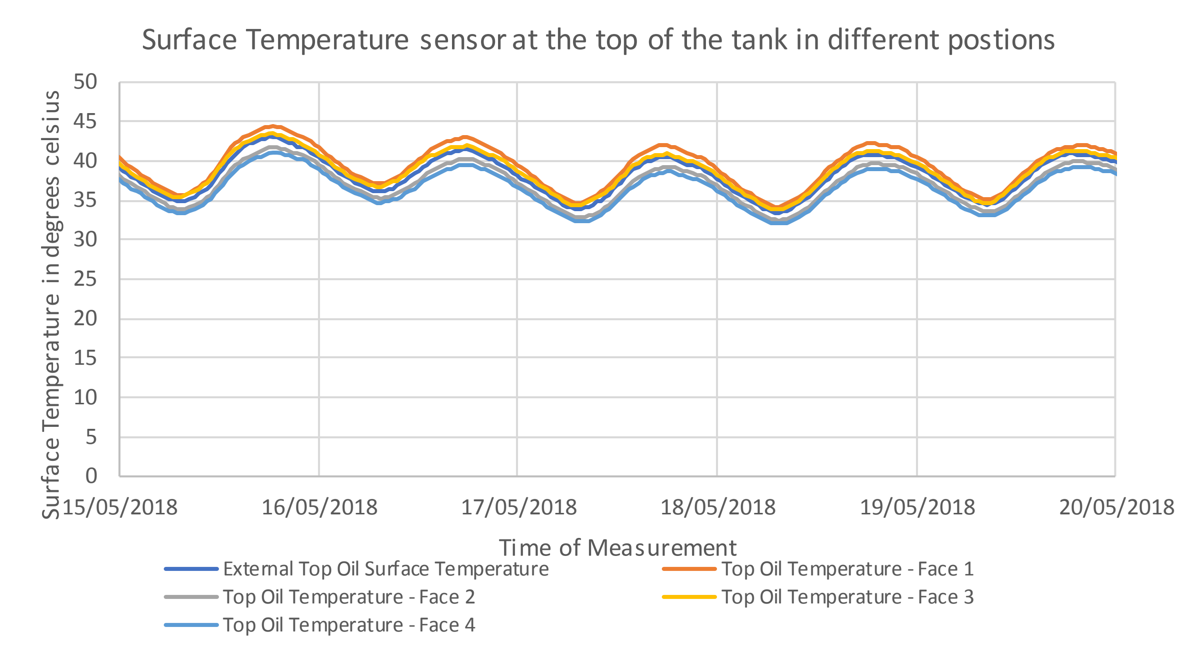

Figure 15: All top oil surface temperature sensors at Kincardine Rd

Each top oil surface temperature was used to predict the hotspot temperature by using the generic model derived in Step 3. Figure 16 shows these calculated hotspot temperatures for Kincardine Road.

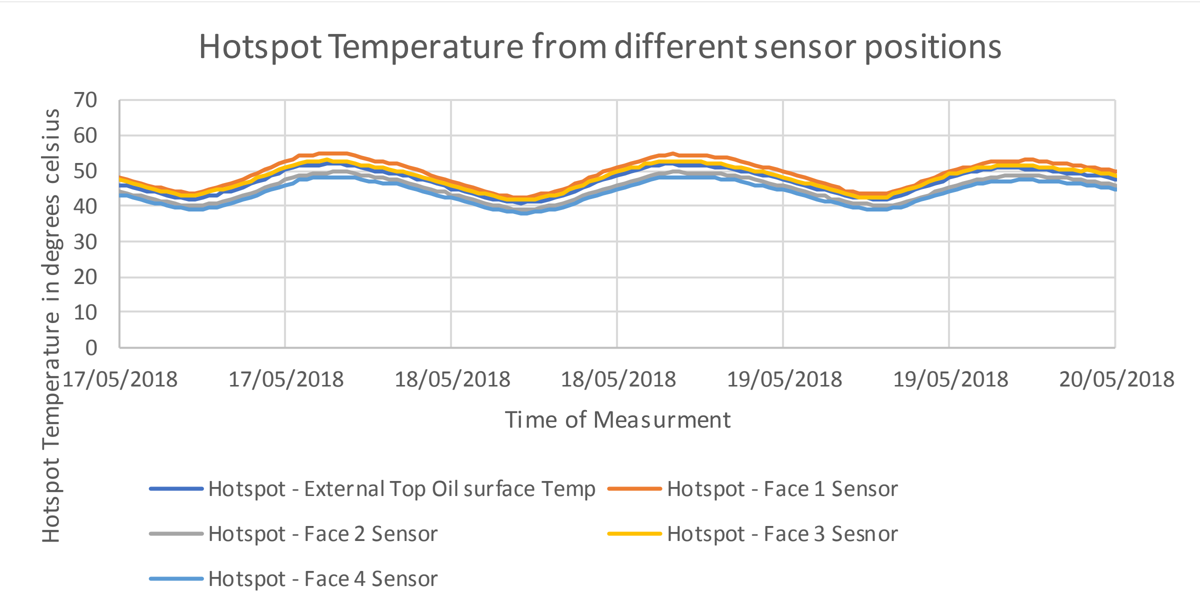

Figure 16: Hotspot temperature obtained as a function of the external top oil surface temperature and the other top oil sensors

For all 17 sites, the estimated hotspot temperature was calculated from each sensor. The difference between each hotspot calculation was compared, using that derived from the sensor adjacent to the internal sensor as a reference, as this is the sensor used to develop the model in Step 2. Again, like Figure 15, there is not a significant difference in the hotspot temperature estimated from each sensor position.

Using data from 14/05/2018 to 14/06/2018, the largest difference in hotspot temperature across all faces at Kincardine Rd was face 4, which was 4.64 °C. This means that using face 4 top oil surface temperature to estimate the hotspot temperature at Kincardine Rd will make the model less accurate compared to using the sensors from the other faces of the transformer.

The box plot diagram in Figure 17 compares the relative differences between the different hotspot calculations from each top oil surface temperature sensor position. The results from all of the short side and the long sides are separated, to compare the performance of each one.

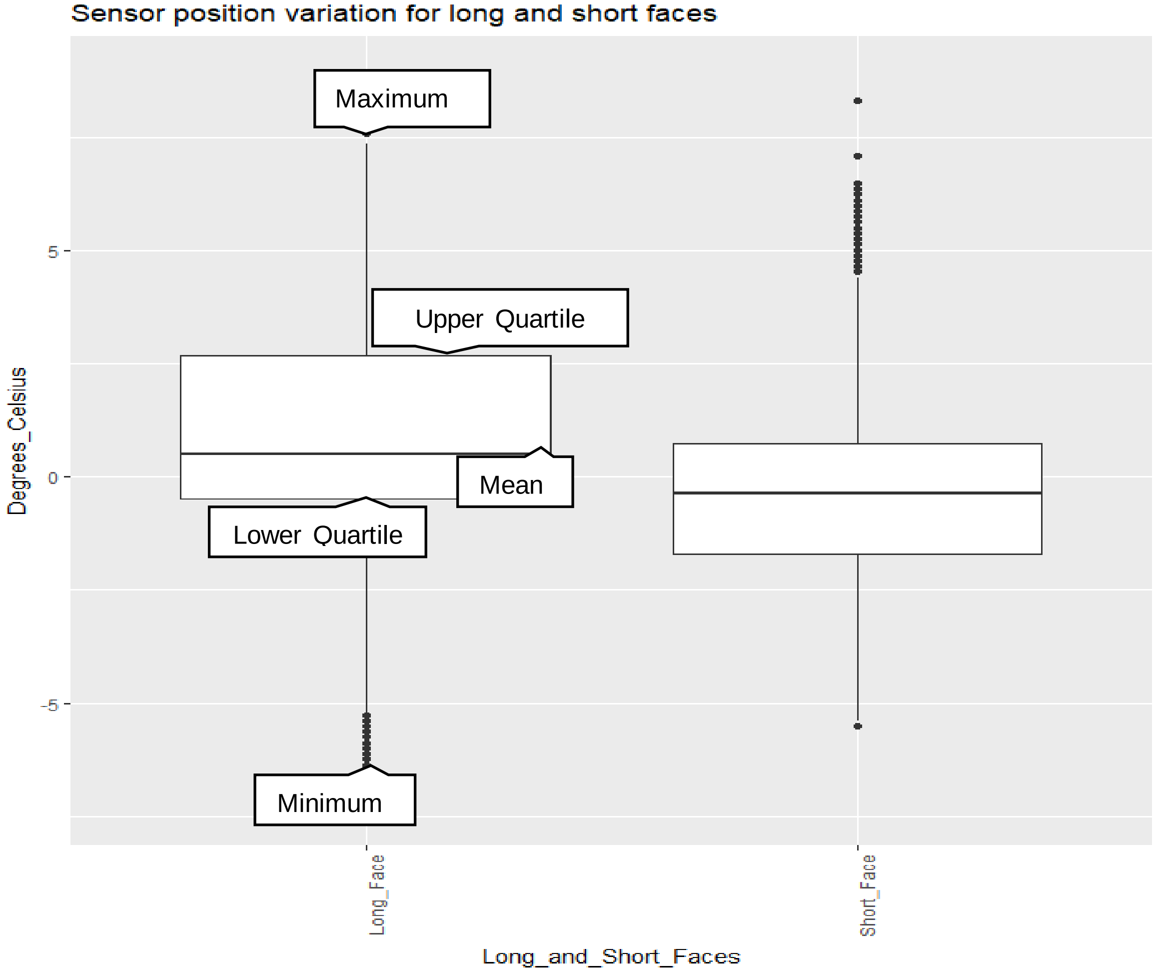

Figure 17: The level of error for estimating the hotspot temperature from surface temperature measured at varied positions, compared to the calculation based on the sensor adjacent to the internal oil sensors

From Figure 17 above, it can be seen that the different sensors generally produce hotspot temperature estimates well within ±5ºC of the reference calculation, and usually within ±2.5ºC. There is a difference in performance between the long and short sides, with the short sides being generally cooler than the long sides, but the difference is not so marked that it could be used as an indicator on its own.

Within the Celsius project and considering that the hotspot estimation methodology is designed to give only an indication of hotspot temperature, this is seen as a reasonable error and no further modifications are required to the hotspot calculation methodology.

A correlation was made between the relative difference in the hotspot temperature from each sensor position and the distance from a nearby corner on the face of the transformer. It was discovered that there is no direct relationship. If the decision is made to deploy sensors for use with the hotspot calculation methodology, it is recommended that they are placed consistently close to a corner where possible, as this is the position that was used to develop the generic model.

2.6.2 Ambient temperature at high level

Similarly, to the top oil surface temperature monitoring, variation in the location of the ambient temperature monitoring at the 17 sites will have an effect on the accuracy of the model. A table showing the heights of the ambient temperature sensor at high levels inside the substation for all 17 sites is shown below:

Site Name	Ambient Sensor Height (m)	Average Error (°C)	Maximum Error (°C)
ABC	2.55	1.78	4.45
Clarendon Rd T2	2.9	3.64	4.2
Dudley ST	2.5	5	5
Helsby Way	2.5	1.61	2.44
Jenny LN	2.3	1.46	3
Jessel CL	2.5	0.63	1.22
Kincardine Rd	2.6	2.06	2.42
Lancaster Ave	2.8	1.3	2.7
Leicester Ave	2.8	2.26	2.69
Mount ST	3.1	0.016	0.23
Offerton DR	2.58	1.046	5
Shackleton CT	2.75	0.016	1
Victoria RD Eccles	2.56	0.55	1.14
Whitefriars	2.7	0.452	1.44
Windsor Rd Prestwich	2.7	1	1.92
Woodend LN	3	1.98	2.46
Wordsworth Rd	3	1.252	3

Table 5: Error in estimating the internal top oil temperature when there is a variation in the ambient sensor height

As can be seen from the table above, the heights vary across all 17 sites. They vary between 2.3 and 3.1 metres. A comparison was made with the ambient temperature sensor variation and the accuracy to estimate the internal top oil temperature.

After doing a correlation test, it was discovered that there is no direct relationship between the position of the ambient temperature sensor and the error in the model. This means that the height is not really an important factor and no further action is needed.

However, it should be noted that positioning sensors close to vents and other sources of heat, such as other equipment, will influence the ambient temperature sensor when it should only take into account the heat coming from the transformer.

2.6.3 Transformer specification

There are 3 transformer specifications defined at this stage of the project (T1, ESI 35-1 & ESI 35-1 UNIT). The T1 type is a historic transformer design dating from the 1960s while ESI 35-1 is the latest transformer design to meet European standards.

The specification information for the Celsius sites was initially gathered from ENW records. However, these records were not always accurate, and many transformers did not have a valid specification on record. The installation process included recording of specification, and this was further checked using photographs of transformer nameplates.

2.7 Transformer Hotspot Estimation Conclusions

Section 2.3 and 2.4 describes the transformer hotspot estimation methodology that will be used through the remaining Celsius data analysis. As mentioned previously, the generic models produced at the start of section 2.5 were validated using the only smart transformer data that was heavily loaded at that time. The generic model estimated hotspot temperature from surface top oil temperature, ambient temperature and transformer specification and was compared to the measured hotspot data on the ihost website. For Kincardine Rd, the period of January 2018 to July 2018 produced error margins between -4.93 °C and 4.98 °C which is within the success criteria. For Clarendon Rd at transformer 2, for 90% of the time, the error was below 5.6 °C.

Note that there are several key limitations to the transformer hotspot study and its results, including:

- **Inadequate smart transformer data** There is only one smart transformer site which has produced consistent, high quality data, and two more have been loaded up to produce data samples which are limited in volume but were used for validation. **Future work could be undertaken to validate and build on the results of this study using more numerous and varied examples of heavily loaded transformers where internal monitoring is available. This could involve installing smart transformers at sites with internal monitoring to a location that can be fully loaded.** This is outside the current scope of the Celsius project.
- **Limitations to the selection of internal monitoring transformers** – The transformers with internal oil monitoring were selected to represent the breadth of site and transformer characteristics across the portfolio. However, due to safety and practical reasons, it was not possible to install internal oil monitoring sensors at outdoor substations or full unit Glass Reinforced Plastic enclosed substations. The result is that while it is possible to make reasonable assumptions about the application of the findings to the wider substation group, some of these applications are not tested. The selection also only includes one example of the unit transformer specification, which will have an impact of the accuracy of this model. **Future work could be undertaken on additional sites covering different building types, outdoor substations, and unit substation specifications.** This is outside the current scope of the Celsius project.

These limitations together have an impact on the confidence with which the outcome of this study, the transformer hotspot temperature calculation methodology, can be used for the remaining analysis within Celsius, including the Transformer Temperature Factors work described in Section 3. The model is within the success criteria most of the time despite the limitations mentioned above. The methodologies developed provide significant insight to the thermal behaviour of transformers, and the conclusions of this analysis are considered strong enough to be suitable for use in the Temperature Factors analysis to develop a robust methodology and draw initial conclusions. It is however, recommended that this analysis be updated when the required additional data described in the bullets above are available. Note that this additional work is not part of the Celsius project.

3. Transformer Daily Temperature Rating

3.1 Approach

The Transformer Daily Thermal Rating Study uses the calculated hotspot temperatures across the Celsius monitoring trial, compares them to measured load, and estimates a rating for each site for each day.

This analysis focuses on the 466 Ground Mounted substation in the Celsius monitoring trial. This section makes use of the expression for predicting the hotspot temperature from surface temperature deduced in section 2. This is a generic expression which can be applied to all sites, noting the limitations described in section 2.7.

The approach for obtaining daily temperature ratings is as follows:

- **Analyse daily data from each site** to determine the statistical relationship between load and hotspot temperature.
- **Estimate the load rating** by estimating the load at which the hotspot temperature would reach the maximum allowable operating temperature.
- **Filter the data** for data quality and high loading to produce a high quality data set upon which to base the next analysis stage.

These stages are explained in more detail in the sections below.

3.2 Daily data from each site

To obtain the transformer's daily rating, the hotspot temperature (calculated using the hotspot temperature estimation equations described in Section 2), and load squared compared for each site and each day, to identify an approximate linear relationship between the two variables. Figure 18 is an example of this.

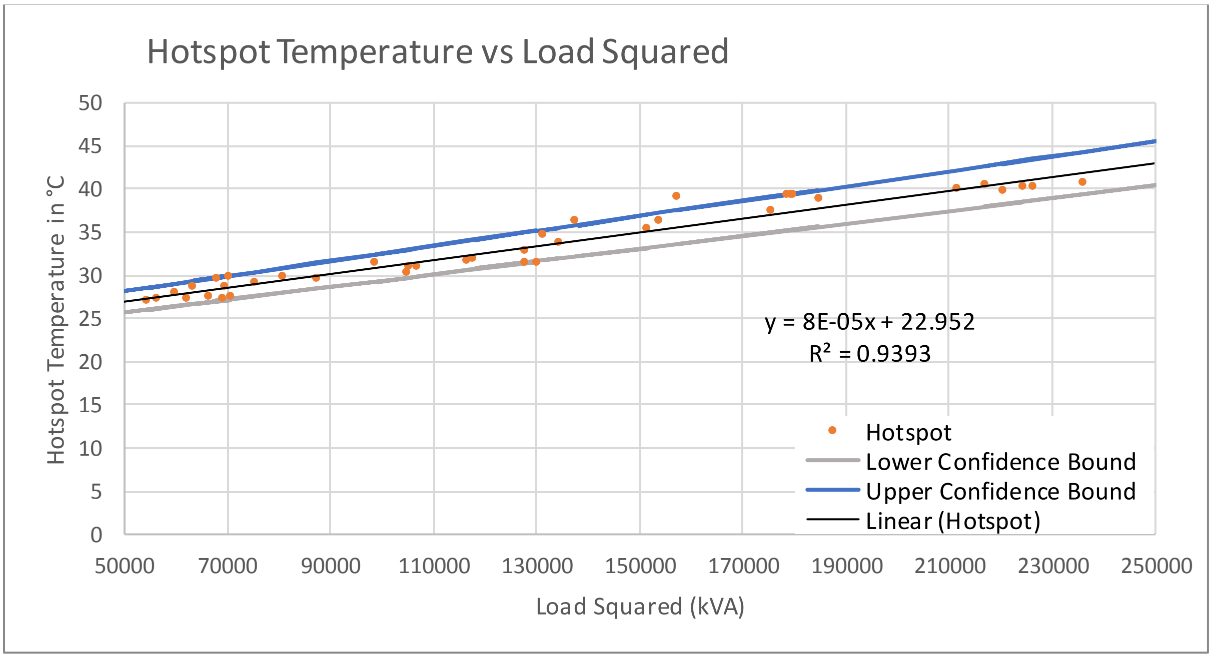

Figure 18: Hotspot temperature vs square of the load for Seaford Rd on the 26/11/2017

The relationship between the heat generated and the square of the load is approximately linear. A line of best fit of the data set in Figure 18 produces the following equation:

$$T_{HS} = 8 * 10^{-5} * S^2 + 22.952$$

Where T_{HS} is the hotspot temperature in °C and S is the load in kVA.

The data does not follow an exact straight line due to its stochastic nature. Therefore, as it is good practise to use error margins with statistical data: 95% confidence intervals were used in this case. These intervals indicate that we could be 95% sure that the data will lie within a certain range.

	Lower 95%	Upper 95%
Intercept	22.03	23.87
S^2 coefficient	$7.37*10^{-5}$	$8.67*10^{-5}$

Table 6: Lower and upper confidence bound equation constants

Therefore, for a given load, we can find with 95% confidence the range of hotspot temperatures.

3.3 Estimating load rating

The thermal rating of a transformer is limited by the maximum operating temperature. The true rating is obtained by finding the value of load at maximum hotspot temperature, above which the transformer would be expected to experience accelerated aging. ENW's transformer code of practice provides maximum operating hotspot temperature for a transformer depending on the load profile, defined simply as continuous, cyclic, and emergency. There are seven load types, but this deliverable will only consider continuous and normal cyclic load types as they cover the non-emergency situations.

Load Type	Temperature Criteria		Pre-fault loading
	Ambient temperature (°C)	Maximum hot spot temperature	
Continuous	Weighted average	98°C	-
Normal Cyclic	Weighted average	105°C	-
Long-Time Emergency Cyclic	Weighted average	115°C	-
3 day Emergency Cyclic	Absolute peak	125°C	-
3 hour Emergency	Absolute peak	125°C	Continuous rating
30 minute Emergency	Absolute peak	130°C	Long-term emergency rating
3 minute Auto Switching*	-	-	Any

Table 7: Maximum hotspot temperature depending on the load type, taken from the ENW code of practice 382; transformer ratings [2]

When determining the maximum hotspot temperature of the transformer it is important to first identify the load type i.e. continuous or normal cyclic. The criterion that defines the difference between normal cyclic and continuous load type is the load factor, f_{Load}, which is calculated using the equation below. For load factors above 83.33%, the load type is considered continuous and vice versa for normal cyclic.

$$f_{Load} = \frac{Total\ Energy}{Peak\ Demand * Hours}$$

Most substations will experience a normal cyclic demand reaching peaks in the evening and troughs after midnight. But with the introduction of smart grid technologies and the push to flatten load profiles, we expect to see more continuous load types in the network. After the filtering process, which is mentioned in section 3.4, there were 20 site days that were classed as having continuous load profiles and 21209 days with normal cyclic load profiles, according to the definition in the ENW code of practice.

For example, the load profile on the 26/11/2017 is inspected to identify its Load Type.

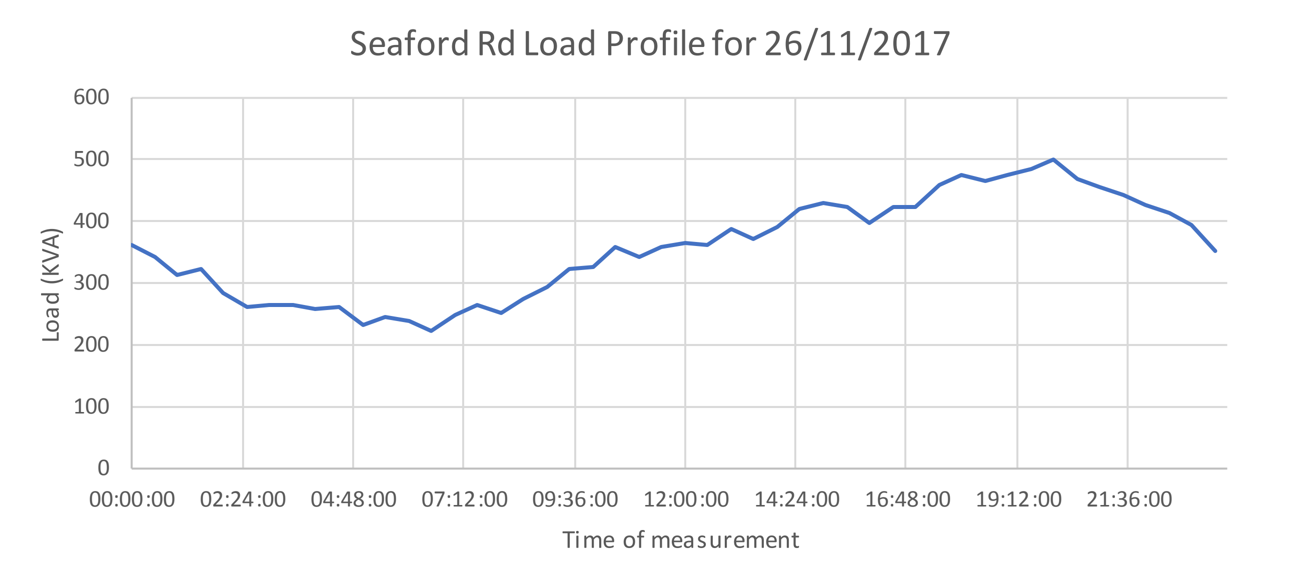

Figure 19: Load profile for Seaford Rd on 26/11/2017

By integrating to find the area under the graph, the total energy is calculated. The peak demand is the graph's peak.

$$f_{Load} = \frac{8384.87\ kWh}{500\ kVA * 24} = 70\%$$

The load type for Seaford Rd on 26/11/2017 is normal cyclic since the load factor is less than 83.33%. The maximum hotspot temperature of the transformer is 105 ℃ for a normal cyclic day as shown in Table 7. In order to calculate a rating for Seaford Rd transformer on the 26/11/2017, the equation in Figure 18 is used to find the value of S at which the hotspot temperature would be 105 ℃. The 95% confidence interval band described in Table 8 was also used to find a high and low value of rating. #these ratings are shown in Table 8 below.

Ratings for Seaford Rd on 26/11/2017	Rating (kVA)
Nominal Rating	800
Celsius Daily Rating – Average	1,012
Celsius Daily Rating – High	1,061
Celsius Daily Rating – Low	967

Table 8: Nominal and daily rating for Seaford on 26/11/2017

The process is carried out for every site and every day. The following is an example of the theoretical ratings over days in November at Seaford Rd (note, only days where utilisation reaches 60% or more are shown).

Date	R Squared Value	Daily Rating - Average (kVA)	% of Nominal Rating
07/11/2017	0.29	1609	201%
12/11/2017	0.79	1283	160%
19/11/2017	0.87	990	123%
20/11/2017	0.71	945	118%
26/11/2017	0.94	1012	127%
27/11/2017	0.40	1618	202%

28/11/2017	0.71	1204	150%
30/11/2017	0.80	987	124%

Table 9: Transformer ratings for days above 60% loaded during November

The table shows that the transformer's daily rating can have a wide variety of values ranging from 945 to 1618 kVA. However, for the two values at which the transformer theoretical rating is exceptionally high (7th and 27th of November), the values of R^2 between hotspot temperature and load are exceptionally low. This could be due to erroneous data, or outside influences, but is not considered to be normal data, and therefore, before any further analysis is carried out, the data is filtered so days with values of R^2 below 0.7 are discarded.

To maintain a reasonable safety margin and ensure safe operation of the equipment, the further analysis to carry out the temperature factor study described in Section 4 uses the low value of daily rating.

3.4 Data Filtering

The aim of the data filtering process is to take out data that is incorrect, incomplete, or not valuable (for example, where the load is very low). This produces a set of data that is high quality and ensures the most valuable results from the next stage of analysis.

For this study, the data is analysed in chunks, each of which covers all of the reported data from a site within a single day. Where data issues are found, the data for a particular site on a particular day can be filtered out, which prevents the results being corrupted, but preserves the rest of the data for use.

There are two key parts to the filtering of this data:

- **Filtering for data quality**
- **Filtering for site loading**

These are detailed in the following sections.

3.4.1 Filtering for data quality

Data quality issues include data gaps (due to issues with the monitoring equipment recording or sending data on site) and reporting of incorrect and corrupt data (where sensors have malfunctioned). It was necessary to automatically detect these issues and apply filters to the data. The filters included:

- **Data gap filter** - Analysing data can be difficult and inaccurate if data is missing. Therefore, a filter was applied to exclude days with more than 4 points missing. As the data is half-hourly, this means that strings with less than 22 hours (out of 24) of data are excluded.
- **Duplicate values filter** – Occasionally, multiple values were recorded for the same time stamp. These sites, such as Clarendon Rd were excluded from the study.
- **Incorrect data filters** – Data was filtered for behaviour that indicates malfunctioning sensors, including values that were out of range, or those with very low correlation between load and temperature.

3.4.2 Filtering for site loading

This study is particularly interested in higher loaded sites as these are the sites that are approaching their operational limits. It is also important that the data set taken forward is representative of the whole portfolio of distribution substation sites. There is a balance to be struck between filtering data for high loaded sites, while retaining enough to represent the key site building types and transformer specifications.

Figure 20 shows the spread of sites categorised based on the transformer rating and the building type. The temperature factors work has shown that these two categories can be considered significant and information about them was readily available.

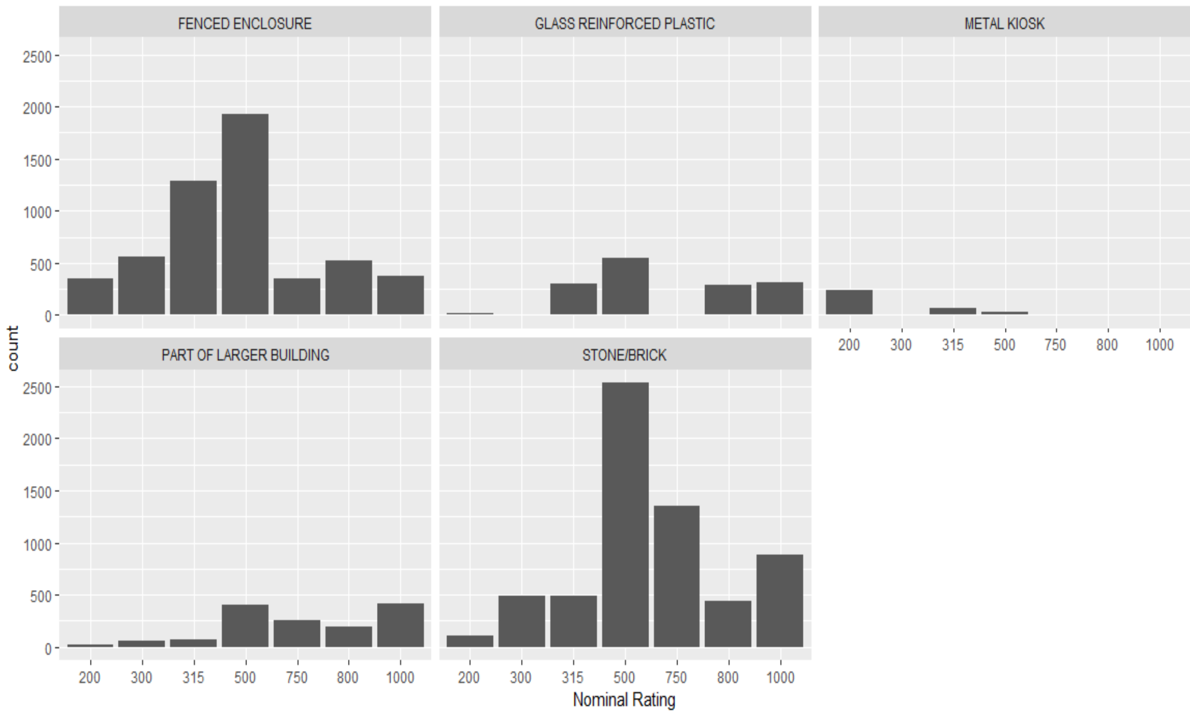

Figure 20: Spread of sites by transformer nominal rating and substation building type for all ENW sites

Figures 21 to 23 shows the spread of data for all sites and days with at least 80%, 70% and 60% loading thresholds. The aim of this is to investigate which set of data to take forward to create the tool.

For 80% (Figure 21), metal kiosk and stone/brick are well represented in the data set. However, substations 'part of a larger building' were not represented at 800 kVA. Fenced enclosures are underrepresented for transformer ratings of 750 and 1000 kVA. GRPs with transformer ratings of 800 kVA are also underrepresented.

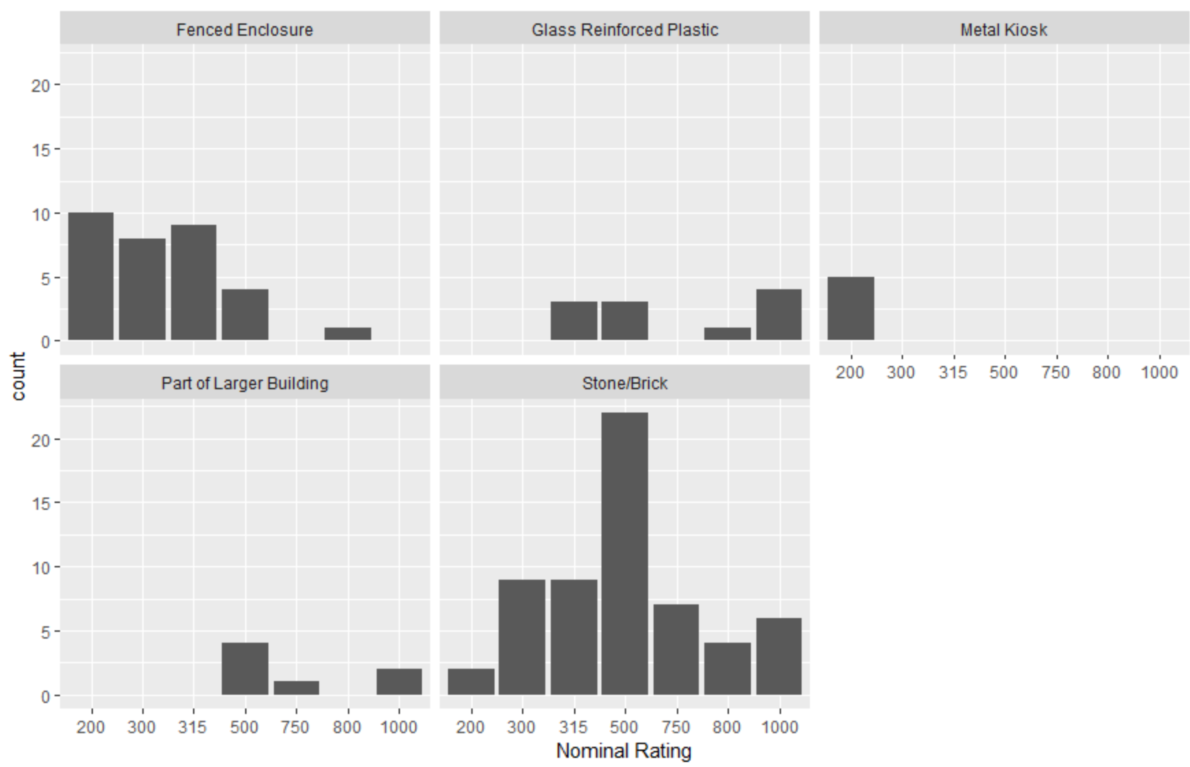

Figure 21: Spread of Celsius sites by building type and transformer nominal rating for all data loaded more than 80% loaded

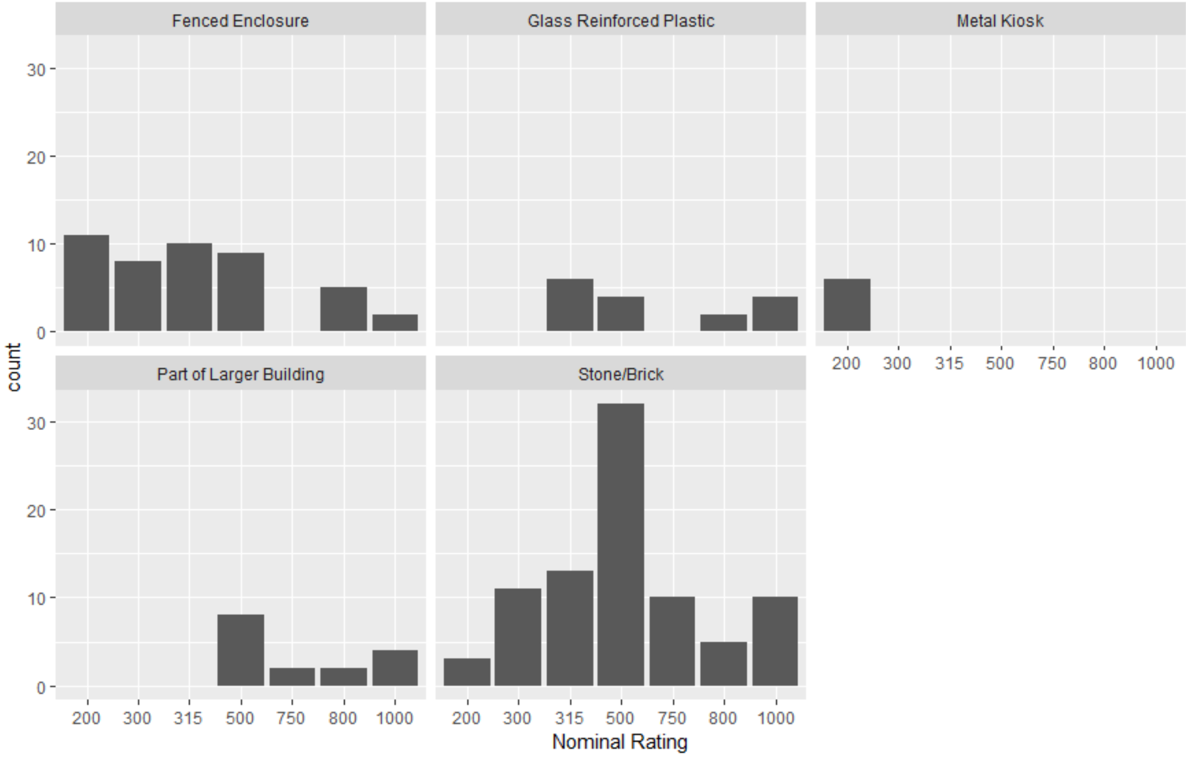

Figure 22: Spread of Celsius sites by building type and transformer nominal rating for all data loaded more than 70% loaded

Figure 22 shows a slight improvement in the representation of the categories. However, we see a better improvement in category representation in Figure 23 when load is above 60%. This data shows a good representation of the whole data set and is taken forward when modelling from hereon in.

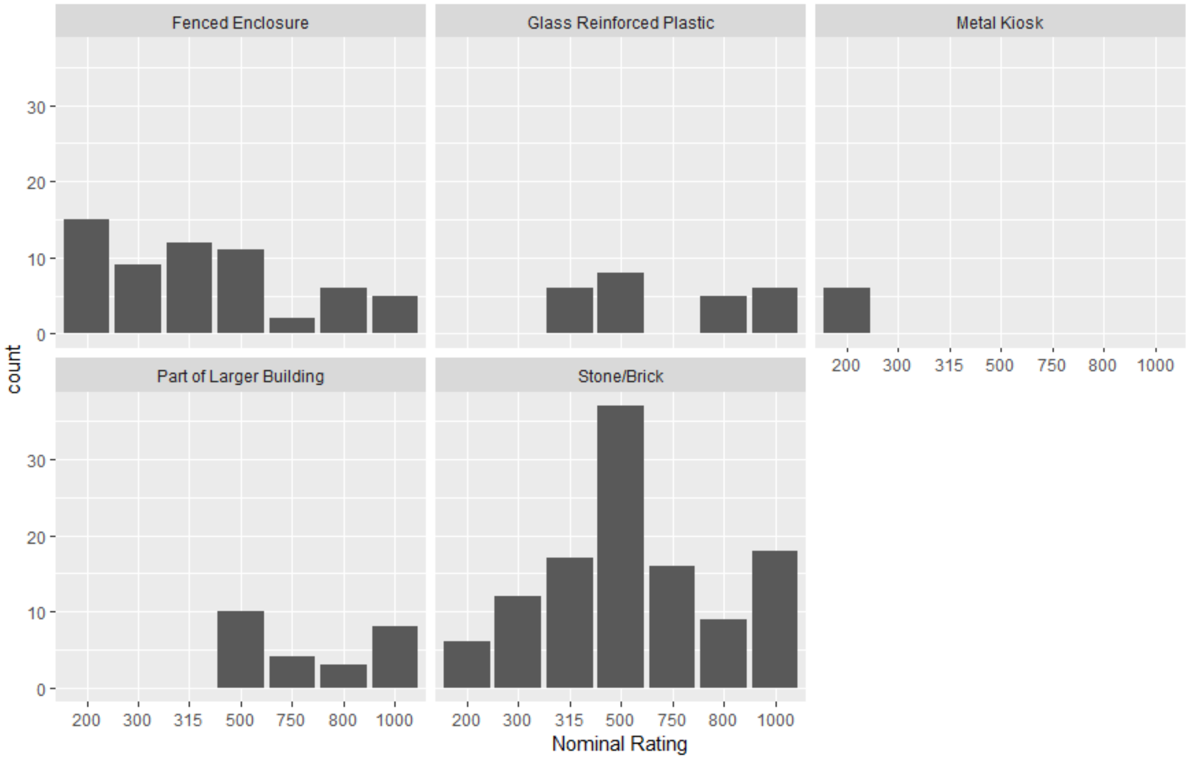

Figure 23: Spread of Celsius sites by building type and transformer nominal rating for all data loaded more than 60% loaded

3.5 Daily Temperature Rating Results

The result of the Transformer Daily Rating study is a set of daily ratings for each Celsius site. The filtering process has ensured that the data is high quality. Out of the roughly 180,000 strings (days) of data that was collected for this analysis, 20,000 pass the filters (12% of the total data), which provides a significant data sample with a good spread that represents the overall data set well. This means that there is a good correlation between the hotspot temperature and load of the transformer for each site at certain days of the year, less data gaps for those days and all sites used in the analysis have a peak load of 60% or more. The daily rating was then calculated and compared to the nominal rating.

Generally, the analysis is carried out by using the lower confidence bound. By using the lower bound we can be 95% confident that the value of S we are using is not an overestimate.

Figure 24 illustrates the difference between Celsius calculated daily transformer rating and the nominal rating.

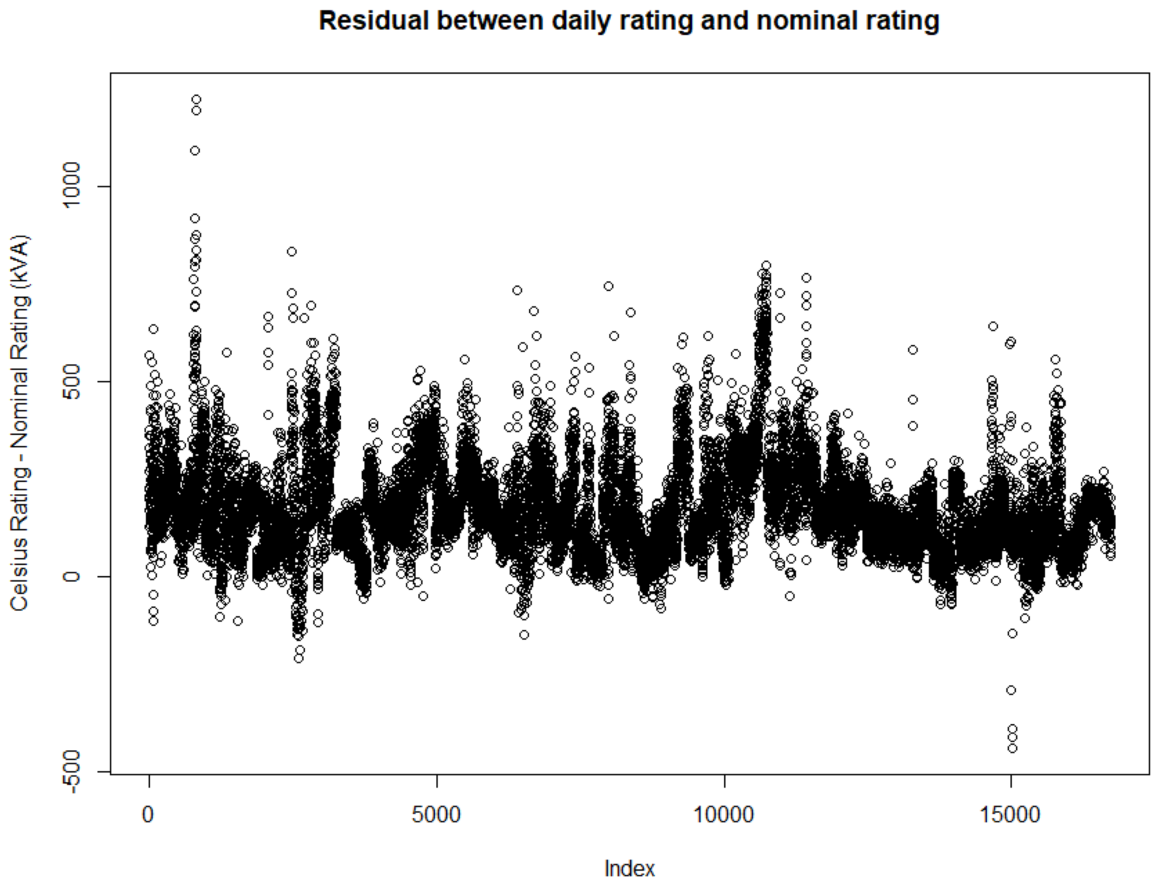

Figure 24: Difference between transformer's nominal rating and calculated daily rating

After removing sites due to data quality issues, a residual between the daily rating and nominal rating for each site and each day was obtained. The data is arranged along the x-axis by site in an arbitrary order. It shows that generally the value of daily rating is higher than the nominal rating. The mean value of this data is 173 kVA. On average there can be 173 kVA of additional capacity available for the LV transformers to operate towards per day per site.

The graph shows some occasions where this delta is particularly high. The table represents the only site over a 3 day period that has delta values greater than 1000kVA.

Site Name	Date	Building Type	Transformer Spec	Nominal Rating (kVA)	Season	Daily rating – nominal rating (kVA)
Beech Ave Irlam	2017-12-23	Stone/Brick	T1	750	Winter	1100
Beech Ave Irlam	2018-02-06	Stone/Brick	T1	750	Winter	1233
Beech Ave Irlam	2018-02-11	Stone/Brick	T1	750	Winter	1204

Table 10: Site on certain days of the year that have a difference in daily rating and nominal rating which is greater than 1000 kVA

There are three cases relating to Beech Avenue, and through further examination of the data it was discovered that these sites have generally high deltas – that is, the Celsius rating is significantly higher than nominal rating, suggesting that the hotspot temperature is cooler than expected for a given load.

There can also be random events, for example, weather causing unusual cooling effects due to wind direction, or impact of external interference such as doors being opened. These events are unusual when viewing the whole of the data from these sites and should not impact the way the site is viewed. This highlights the need to use data across multiple days, over a sustained period of time, to gain a balanced view of the rating. A single day of data may produce misleading results.

There are some occasions when the daily rating is lower than the nominal rating. This represents a total of 34 sites and 373 days that produce a daily rating less than the nominal rating. After further analysis, these fall into two key categories:

- **Cases where daily rating is approximately in line with nominal rating** – Cases where the daily rating is close to nominal rating and dips below in some cases. This is likely to be due to external factors such as weather conditions. The graph below shows an example of this case – note that the gaps in the data are where data has been filtered out as described in Section 3.4. The likely impact of this category of sites is low, as the days where the site has a daily rating lower than nominal rating are generally a low proportion, and the difference between the two ratings is generally small. This is the case for the following sites:
    - ABC Ardwick
    - Alexandra Rd S
    - ATE Grimsargh
    - Berry LN
    - Boyle ST
    - Burghley DR, Bradley Fold
    - Concorde Way
    - Crosthwaite CT
    - Disley Main
    - Dunscore RD
    - Gleneagles RD
    - Green LN
    - Greenside LN Fiveways
    - Helmside Drive
    - Lennons
    - Lorne ST
    - Manor RD
    - Maple Ave
    - Marsland RD
    - Mayor ST
    - Ramillies Ave
    - Regent Street
    - Saunders Wood
    - School LN Standish
    - Sherwood DR
    - Silverwood Ave
    - Summervale HS
    - Temple RD N
    - Wellington RD
    - Wentworth RD

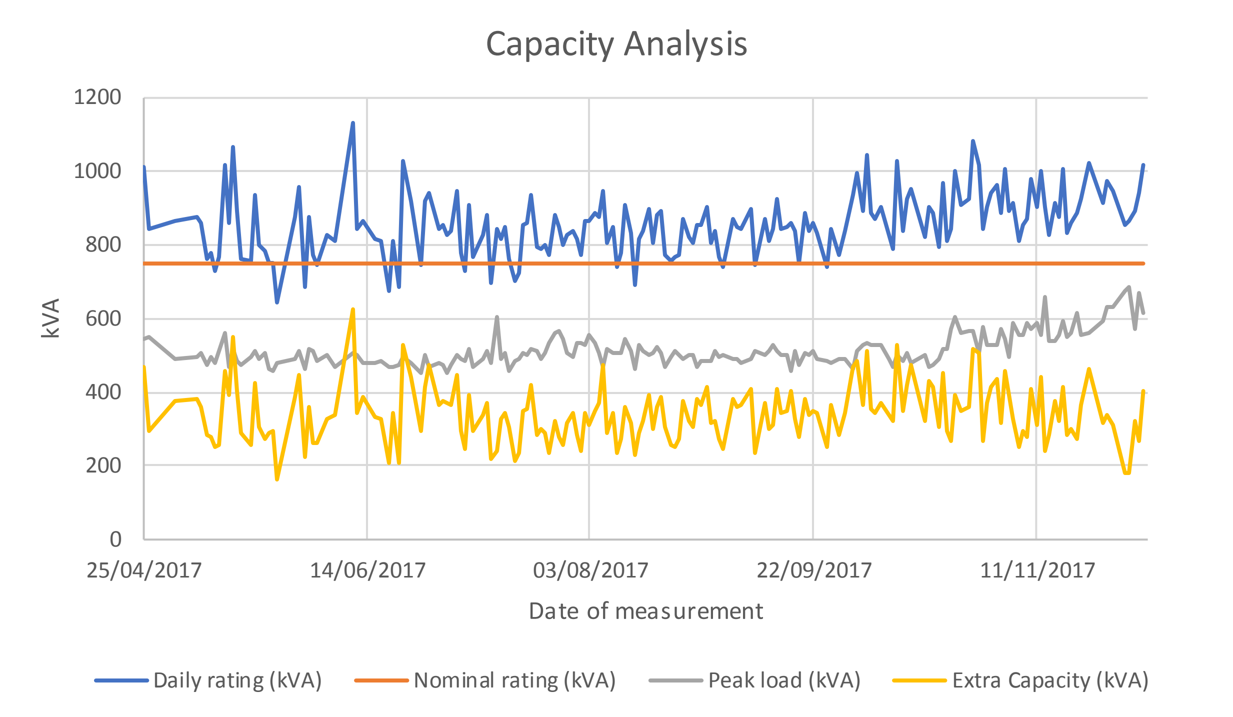

Figure 25: Daily rating and nominal rating data for St. Johns Street substation - this is an example of a case where the daily rating is close to, and occasionally less than, the nominal rating– note that the gaps in the data are where data has been filtered out as described in Section 3.4.

- **Daily rating falls below nominal rating seasonally** – Many sites have a daily rating which is quite seasonal, and in some sites, this seasonal effect on daily rating brings the daily rating bellow nominal rating. For all of these example, the rating falls in summer, which is expected as there is a reduction in natural cooling due to the higher ambient temperatures. It is important that these sites are identified, and loaded carefully. The sites within this category include:
  - Moss Ln
  - St Wilfrids Church
  - Tesco Sale

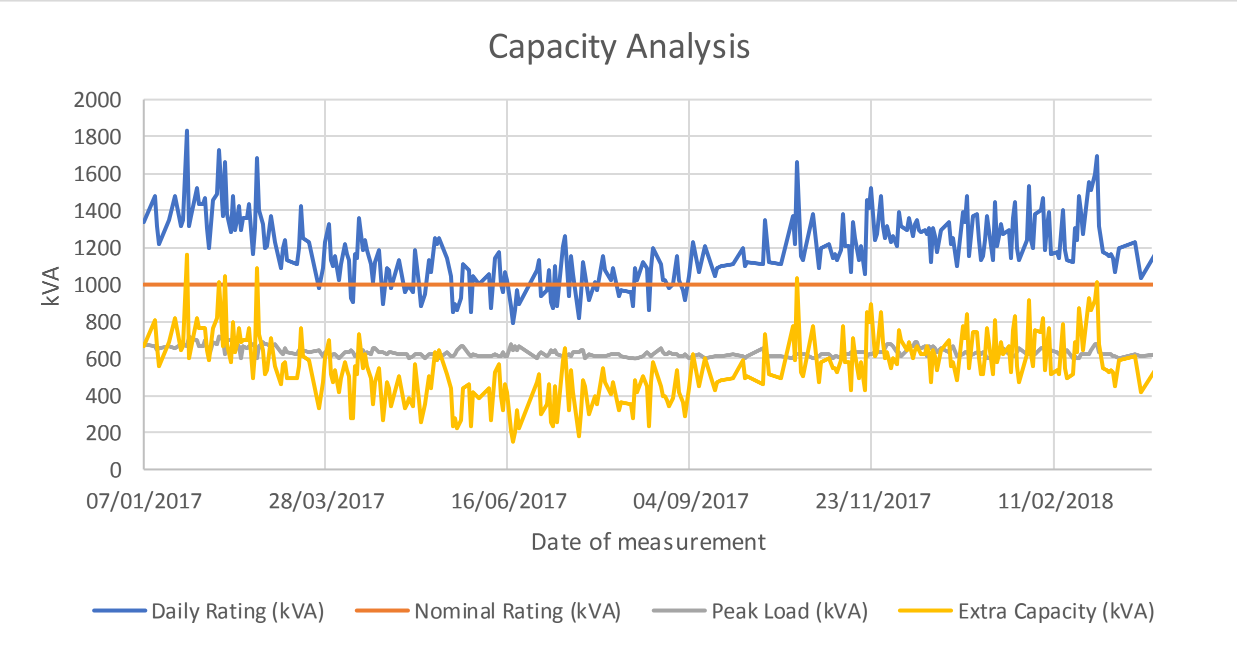

Figure 26: Daily rating and nominal rating data for Tesco Sale substation - this is an example of where seasonal impact on daily rating means that the summer daily ratings are often below nominal rating– note that the gaps in the data are where data has been filtered out as described in Section 3.4.

4. Temperature Factor Analysis

This section outlines the methodology used to obtain a relationship between transformer rating and temperature factor. This analysis uses as inputs the daily ratings that are described in Section 3, and the various transformer and site information and monitoring data collected during the Celsius trial. This section outlines this process in more detail.

4.1 Identifying the major temperature factors

The first stage in the analysis was to identify all the major environmental and loading factors that could have an influence on the hotspot temperature and hence the transformer's daily rating, and that have suitable data and information available to the Celsius project.

The factors that were considered in this study fall under three categories; load conditions, transformer characteristics, and site characteristics. The following lists all the factors taken into account during the course of this study.

- Load Conditions:
  - Load Profile
  - Harmonics
  - Time of peak load
  - Load Factor
- Site Characteristics:
  - Substation building type (for example, brick, glass reinforces plastic, fenced enclosure)
  - Site location (latitude)
  - Site layout (including number of transformers, unit substation)
  - Site ventilation
- Transformer Characteristics:
  - Nominal Rating
  - Age of the transformer
  - Transformer specification (T1, ESI 35-1)
- Environment Characteristics:
  - Season
  - Wind Speed
  - Precipitation
  - Weather Temperature

The following sections of this report outline how the different sites were categorised when considering each temperature factor as well as how the required information was obtained.

4.1.1 Load Profile

A load profile is the shape of the load over a day. Distribution substations experience different load profiles depending on the category of load they serve (e.g. domestic, commercial, industrial, or a mixture), and may experience different load profiles on different days of the week and times of the year.

The Celsius load data (total apparent power) was analysed to produce generic load profile categories using a normalising and clustering method, using the K-means method. The key steps are outlined below:

4.1.1.1 Normalisation

The data was normalised within each day's readings. All readings have been scaled using the maximum reading on the day set to 1. Thus, all hourly readings are in the range 0-1. The effect of this normalisation is to focus on the shape of the usage pattern and not on the total usage.

Two households with a similar shape but with differing total usages (e.g. if one household is much larger than the other) may have the same normalised load profile once scaled. As a consequence, the clustering algorithm can compare the consumption habits from two households or commercial areas of different sizes.

4.1.1.2 The Clustering Method

Research undertaken about clustering algorithms identified the K-means method as an appropriate solution for clustering the normalised load profiles. This method of load profile classification was used in the UK Power Networks Distribution Network Visibility Project.

The K-means method requires a number of clusters as an input parameter and works by randomly selecting an initial n location for the centres of the clusters. Each data point is then assigned to one of the centre locations by selecting the centre that is nearest to that data point. Once all the data points are assigned, each collection of points is considered. A new centre of the allocated points is calculated and the centre for that cluster is reassigned. The K-means method uses Euclidean distance calculated for centre c = (c_1; c_2; ...; c_n) and point p = (p_1; p_2; ...; p_n) as

$$distance = \sqrt{\sum_i (c_i - p_i)^2}$$

The points are then reallocated to their new nearest centre and the algorithm continues as before until no changes are made to the allocations of points between iterations. The K-means algorithm returns the n centres of the clusters (called centroids), and the classification of each point in the cluster it belongs to.

The method is highly dependent on the initial random allocation of centres. To avoid this issue which gives rise to different results every time the clustering method is executed, the program was run 25 times with random centroids and the one with the least Mean Square Error was chosen.

4.1.1.3 Optimisation

As seen above, the K-means method requires a number of clusters as an input parameter. As we expect, the more clusters we choose, the more accurate the output will be, as the points will be closer to the centroid of the cluster they belong to. The extreme case is a number of clusters n equal to the number of points; in this case each point will be in its own cluster.

The optimal number of clusters is ambiguous and depends on the shapes and the number of the points on which the algorithm is applied. A good clustering scheme will create clusters where the members of a particular cluster are closely grouped, but where the different clusters are well separated. The method chosen to determine the optimal number of clusters uses a measure assessing the quality of the clusters generated: the Mean Index Adequacy (MIA):

$$MIA = \sqrt{\frac{1}{K}\sum_{k=1}^{K} d^2(r^{(k)}, C^{(k)})}$$

Where K is the number of clusters defined, $r^{(k)}$ is one of the load profiles assigned to cluster number k, and $C^{(k)}$ is the centroid of the cluster k. The optimal number of clusters should be chosen so that adding another cluster does not give a much better modelling of the data. Figure 27 shows the MIA decreases a lot as the number of clusters increases from 1 to 4, and progressively the marginal gains drop by adding a cluster. Therefore, 4 clusters were used for the optimisation.

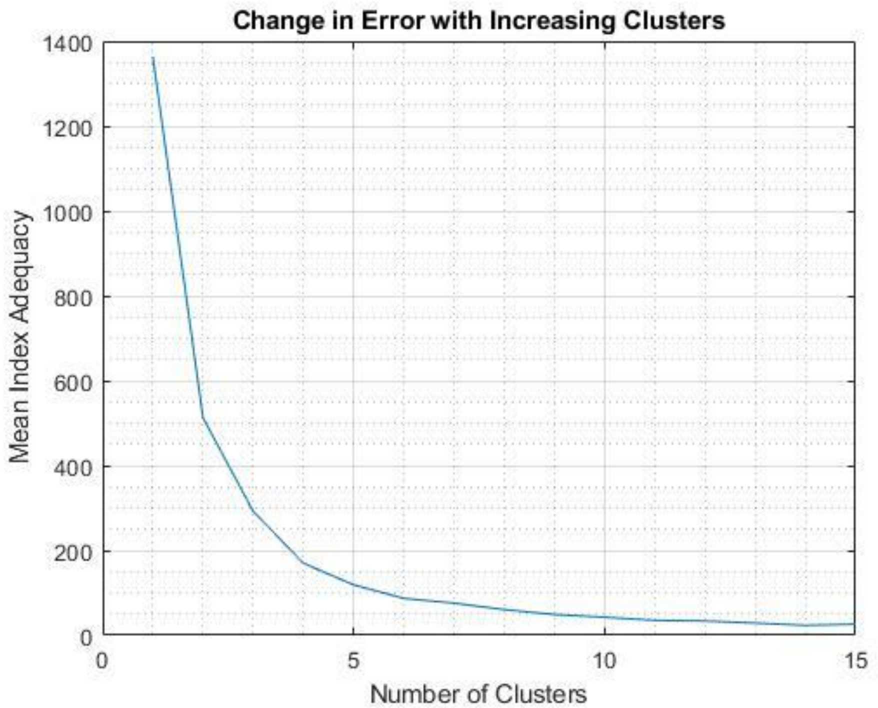

Figure 27: Change in Error with increasing Clusters

4.1.1.4 Results

Consequently, Figure 28 shows the four load profiles that represent 1 year's data from all sites with three phase power monitoring data. The clusters are named load profile 1 to 4.

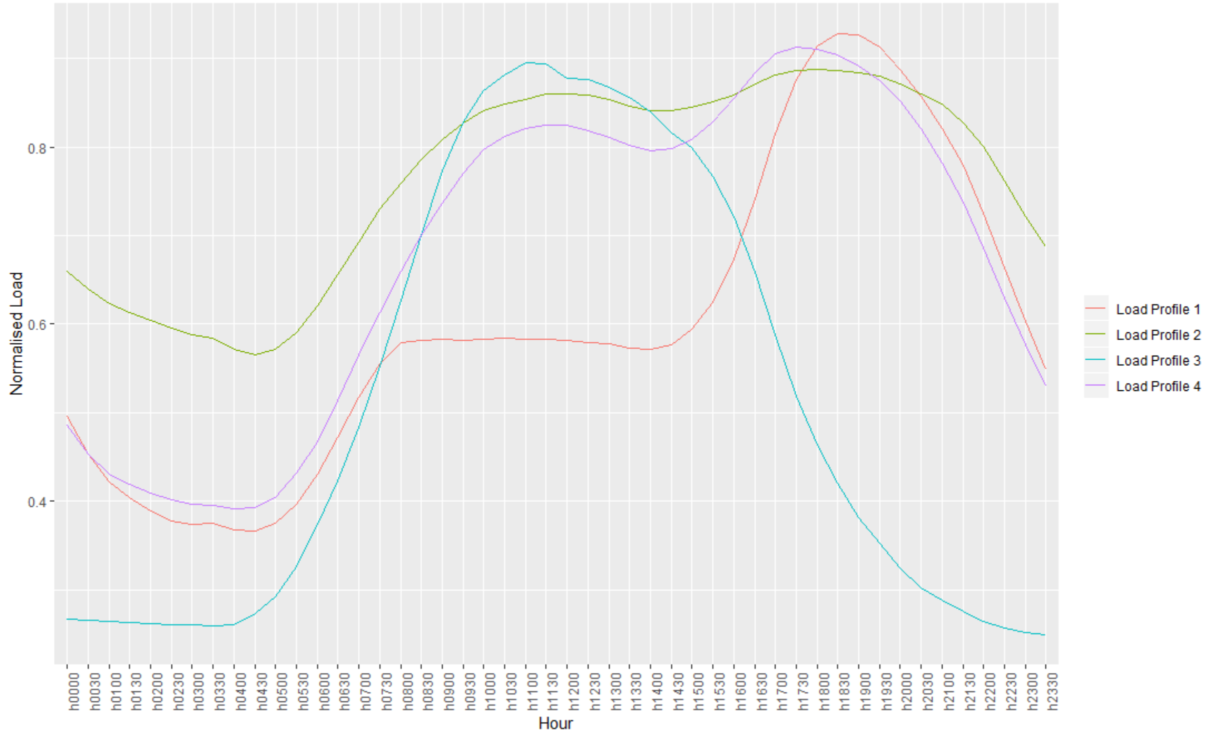

Figure 28: Number of clusters used for load profile

The 4 clusters are general representations of the typical load profile on ENW's distribution transformer. Load profile 1 peaks at approximately 20:00 hours which represents a typical residential area. Load profile 2 represents the flattest load profile peaking for long hours during the day. Load profile 3 peaks at around 11:00 hours, and represents a day loading profile. Load profile 4 is similar to load profile 1 in that it peaks twice a day during midday and at 17:30 hours, but is flatter than load profile 1.

These conclusions were applied across the whole Celsius trial portfolio by determining the load profile cluster for each site and for each day. For the sites with single phase monitoring, the total load of the site is estimated by multiplying the single phase apparent power by three.

4.1.2 Harmonics

Current harmonics are measured for every site. Harmonics are expressed as a measure of total harmonic distortion (THD). This is defined and calculated by the following equation:

$$THD = \frac{\sqrt{{I_2}^2 + {I_3}^2 + \cdots + {I_{25}}^2}}{I_1}$$

Where I_n is the RMS current of the n^{th} harmonic and n=1 is the fundamental frequency (50 Hz). At each site, the hex unit calculates the total harmonic distortion by measuring the harmonics up to the 25^{th} order.

As mentioned previously, there are sites with three phase monitoring, and sites with single phase monitoring within the Celsius trial. The sites with three phase monitoring report a THD for each phase, while the single phase monitored sites report THD only for the monitored phase.

4.1.3 Peak Load Time

This temperature factor specifically focuses on the peak load of the transformer. The peak load is the most critical part of the load profile and the time of the peak during the day can influence the temperature of the transformer. For example, a transformer that peaks in the early mornings (coolest part of the day) may have a lower hotspot temperature than a transformer that peaks in the afternoon (the hottest time of the day). This temperature factor gives a time for the occurrence of peak load and is measured with a 24 hour clock. The following graph shows the spread of peak load time. The y-axis shows the number of occurrences. The majority of peaks occur during dinner time and a small minority occur during lunch time. This Figure below shows that there are very few sites with a night peaking load included in the analysis.

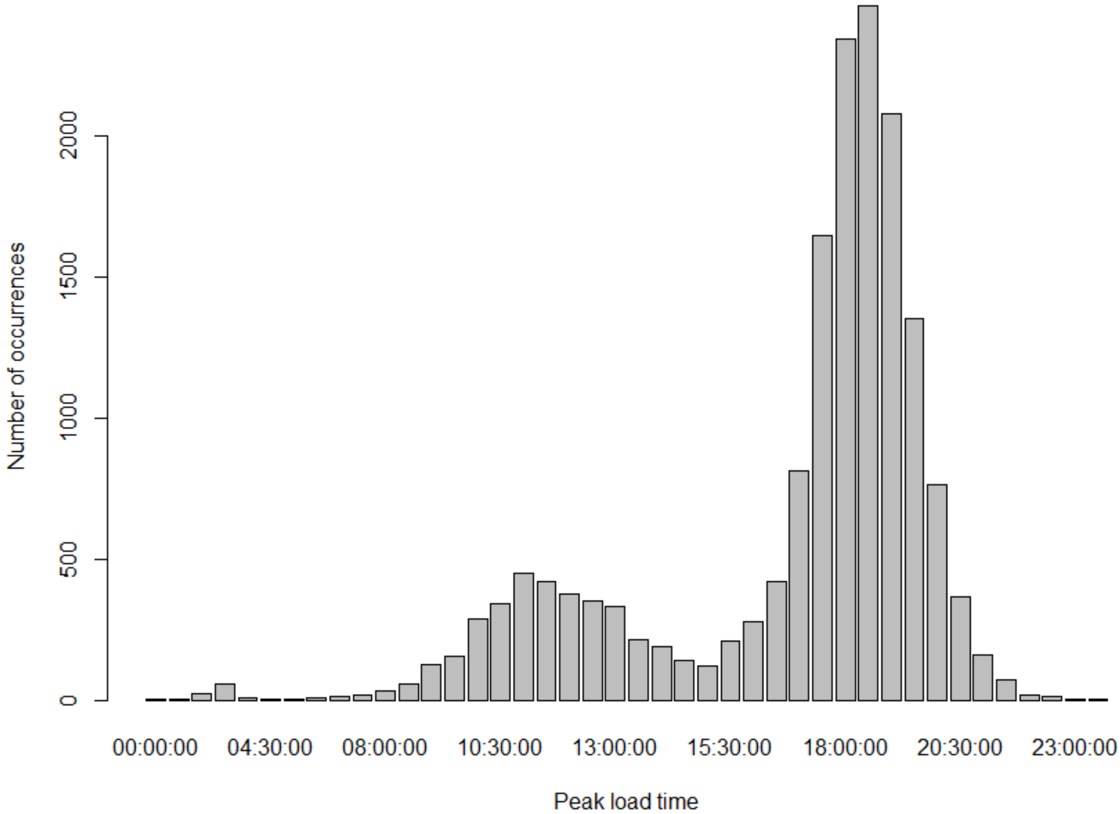

Figure 29: Spread of time peak load for daily load profiles

4.1.4 Load Factor

The load factor is a measure of utilisation of the transformer and is defined as the ratio of the total load to the peak load, as shown in the equation below. A high load factor indicates constant energy usage and low load factor indicates peaky usage. Given that we have filtered for highly loaded transformers, it is expected that higher load factors will create more heat in the transformer than low load factors.

$$f_{Load} = \frac{Total\ Energy}{Peak\ Demand * Hours}$$

4.1.5 Building Type

The sites were each categorised into the following building types;

- Fenced Enclosure (outdoor),
- Glass Reinforced Plastic,
- Part of larger building,
- Stone/brick,
- Metal Kiosk

Table 11 illustrates some of the building types above.

Building Types	
Fenced Enclosure 	Glass Reinforced Plastic 
Stone/Brick 	Part of a Larger Building 

Table 11: Different Building Types

The building type could have a significant impact on the ambient temperature of the asset's operating environment. An outdoor transformer will experience more wind than an enclosed transformer. The wind cooling in this situation could result in higher operational limits for outdoor transformers. The opposite could be said during the summer when the outdoor transformer is exposed to the sun while the enclosed transformer is protected. For this reason, it has been determined that the building type could be an important temperature factor to investigate.

4.1.6 Latitude

The latitude of each site were found using GPS and stored on the Celsius server. We expect that location can make a difference on the operational limit of assets, as it may indicate different weather conditions and different environments. However the initial analysis of latitude did not produce significant results and was subsequently removed from the analysis. The range of latitude numbers across all ENW sites are similar and this produced misleading results.

4.1.7 Site Layout

The sites that are being investigated have a range of site layouts which could potentially have an impact on the hotspot temperature. For example, unit transformer sites have equipment tightly packed together which could result in heat being transferred between units, and sites with two transformers may have increased ambient temperatures as there is an additional major heat source in the room.

4.1.8 Site Ventilation

This temperature factor simply indicates if the substation has ventilation or not or if the transformer is outdoors. The three choices in this category are;

- Has ventilation
- Has no ventilation
- Outdoors

These categories were recorded for each site during installation. Ventilation is expected to influence the transformer's temperature as ventilation could reduce ambient temperature within a substation drastically.

It is recognised that the existence of ventilation is no indication of how effective it is, for example, ventilation could be inadequate or blocked. Investigations were carried out into ways of categorising ventilation, for example using data collected about the ventilation inlet and outlet temperatures, however this investigation did not produce significant results and therefore has been omitted from this report.

From further investigation, ventilation was also removed from the analysis because of data quality issues.

4.1.9 Nominal Rating

The nominal rating of a transformer is the rating that the manufacturer has assigned to it and can be found on the transformer nameplate. It is a key indicator of the design capacity of the transformer, and therefore is likely to be a driving factor to determining the more informed Celsius rating. This information was gathered from ENW records and confirmed during the installation process.

4.1.10 Age

The age of an asset can have significant effect on its operational efficiency. Assets can suffer from wear and tear, material and oil degrading and eventually malfunction after a certain period. Clearly, there are external factors that can accelerate the process of ageing such as its loading conditions, environment, and the number of times it has been maintained.

The data available for the Celsius project is the manufacture year, which is available from transformer nameplates. This information was gathered from ENW records and confirmed during the installation process.

4.1.11 Transformer Type

There are 3 transformer specification types that every site that is of interest in the Celsius project can be categorised into. These are as follows:

- **T1** – Older British Standard specification and represents transformers that were manufactured from 1929 onwards.
- **ESI 35-1** – Newer European standards that have been installed since the 1970s.

This information was gathered from ENW records and confirmed during the installation process.

4.1.12 Season

The season indicates what season of the year it is. There are four categories depending on the date;

- Winter – From December to February
- Spring – From March to May
- Summer – From June to August
- Autumn – From September to November

The season is another temperature factor that will affect ambient temperature of the substation and consequently the transformer's daily rating.

4.1.13 Wind Speed

The wind speed indicates the intensity of the wind in the area of the transformer substation. Transformers experiencing high levels of wind may have a higher rate of heat dissipation due to convection. Data for this variable is provided from the MET office and is measured in m/s.

4.1.14 Precipitation

The precipitation measures the levels of rain or snow in the area and is measured in mm. Rain that falls on top of substations or outdoor transformers is expected to cool down these assets. Data for this variable is provided from the MET office.

4.1.15 Temperature

The weather temperature in the area is expected to directly affect the hotspot temperature of the transformer. Data for this variable is provided from the MET office and is measured in ºC.

4.1.16 Other Factors

It Is recognised that there are other factors that may have an effect on the operating temperature of assets. These include for example, solar radiation, immediate surroundings, oil condition and operation history of equipment. These factors were not included in the analysis because data was not available to support this. If data becomes available at a later date, then the analysis could be easily updated to include it. Note, this further work is not part of the Celsius project as defined.

4.2 Temperature Factors Investigation

The Temperature Factors Analysis aimed to develop a model for the transformer daily rating from the various temperature factors listed above.

Figure 30 shows the results of the analysis to determine the best model based on all of the factors listed above. The analysis identifies the most influential factor to build a model, and then calculates a correlation coefficient, R^2, between the results of this model and the calculated daily ratings. The analysis then determines, given the model it has, what is the next most influential factor, and calculated the new value of R^2. This continues until all factors are used.

In Figure 30, the left most data point is the R^2 for a model based only on the most influential factor, the nominal rating, while the right most data point is the correlation coefficient for a model that includes all of the factors.

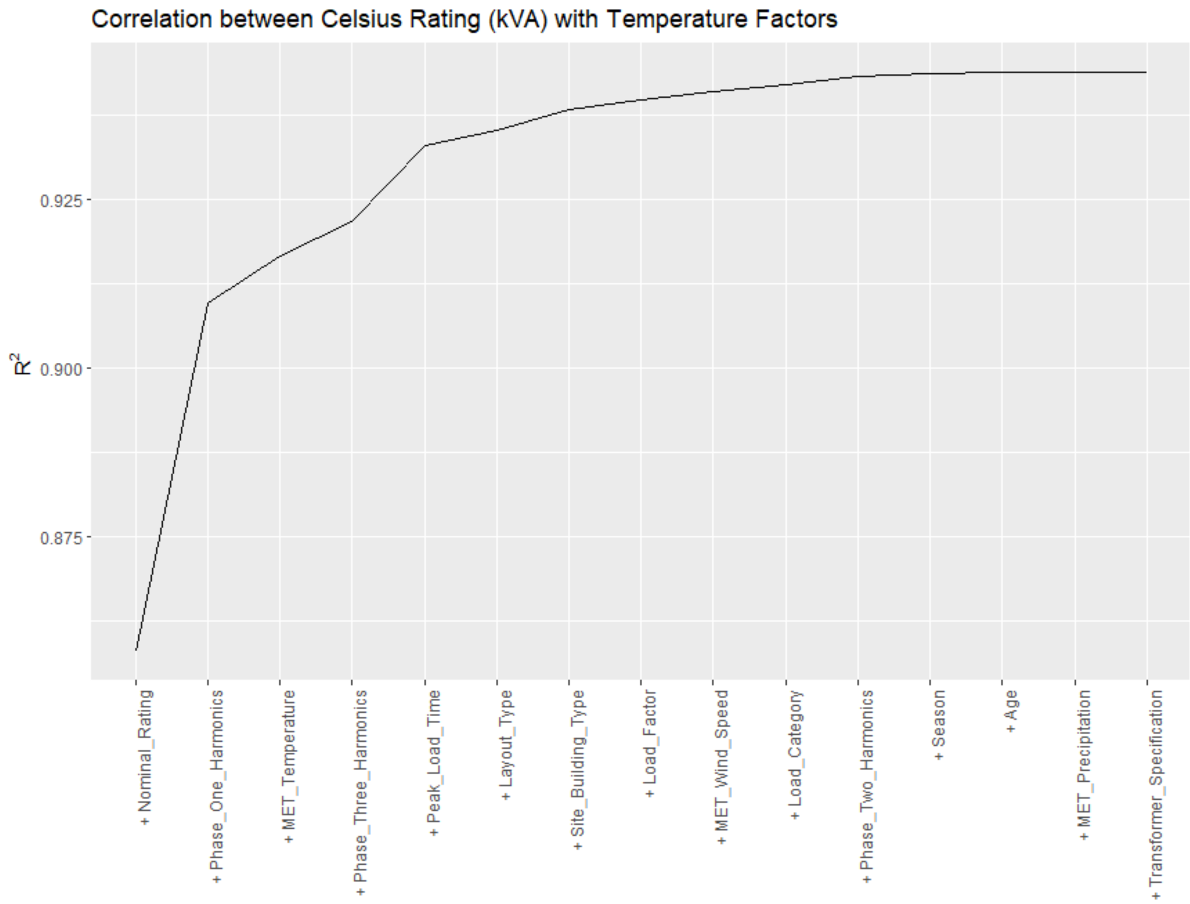

Figure 30: Correlation coefficient of daily rating as temperature factors are increased

The correlation coefficient increases as more temperature factors are added. The correlation coefficient for the model that includes all the temperature factors reaches more than 0.94, which indicates that the modelled rating has a very good match with the calculated daily rating.

The factors shown on the left of the graph, that have the most influence, are:

- **Nominal rating** – this is expected to have a significant influence, as the size and capacity of the transformer should be a key guide to how much load it can carry.
- **Current Harmonics** – it is expected that the current harmonics would influence rating, as high harmonics will have a heating effect. Note that the current harmonic data is shown as three different factors as many sites have all three phases measured. The fact that they are not all influential is an example of how factors that are closely related to each other can be less influential as they do not provide additional value to the model.
- **Weather**–the temperature outside will have an influence on the ambient temperature inside the substation, and on the ability for heat to escape from substations and asset surfaces.
- **Peak Load Time** – the time of the day that the site reaches peak load is influential, as a peak load at night will have more natural cooling from the cooler ambient, whereas peaking during the day coincides with the warmest ambient and the potential for solar gain.
- **Layout Type** – the layout of the transformer will have an influence. This suggests that the daily rating at sites, where the transformer is separate to the LV board and RMU, will behave differently to a full unit or two transformers and should be taking into account when assigning daily ratings
- **Building Type** – the structure of the substation will influence the selection of a daily rating value. Substations which are outdoor will be exposed to more wind compared to enclosed substations, which can provide natural cooling. Brick built substations have more thermal mass, and so behave differently to GRP substations.

The factors that are the least influential include transformer age, specification, precipitation, and load profile. This indicates that these categories do not add significant additional value to the model, for example because they do not have a significant correlation with daily rating, or because they are closely related to another factor that is already included in the model.

Perhaps the most surprising factor in this list of least influential factors is load profile. It is accepted knowledge that the load profile is likely to influence the rating of a transformer. The placement of this factor on the graph is likely to be influenced by the fact that the daily rating itself is calculated taking into account the difference between continuous and normal cyclic load profiles. There is a total of 20 days that are continuous and 21209 days that are normal cyclic. Another influential issue is that the daily load profiles that were determined (see Section 4.1.1) are not particularly varied, due to the fact that that the trial does not include sites with more extreme loading profiles, for example night loading. Therefore, the impact of the differences between the relatively similar load profiles determines are not significant.

The rating model developed is intended for use with sites where there is no real time data available; where it is possible to install monitoring equipment and bring data back, the daily rating method can be used directly and there is no need to use a model to estimate it. For this reason, all temperature factors that require real time measurements such as harmonics, peak load time, weather temperature, wind speed, precipitation and load category are removed from the analysis. The correlation coefficient was recalculated to produce the following graph.

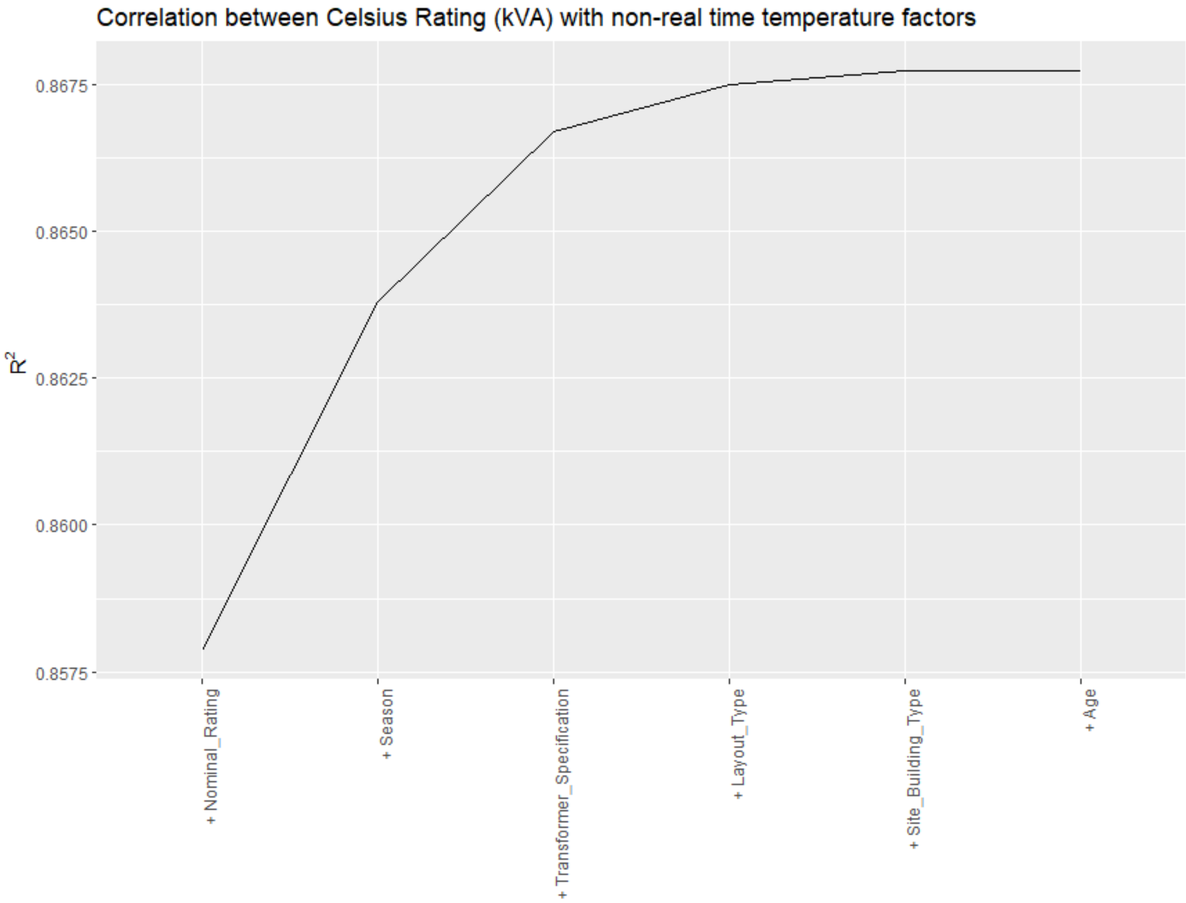

Figure 31: Correlation coefficient of daily rating as temperature factors are increased, excluding current harmonics

The result of this analysis shows that the removal of real time temperature factors still leaves a good model, with an R^2 ranging between 0.85 and 0.87. The site building type along with layout type has a very small influence but the fact that it still has a degree of influence on daily rating meant that it was still considered. The inclusion of site age has no influence on the relationship and was removed from the analysis. The final graph is as follows:

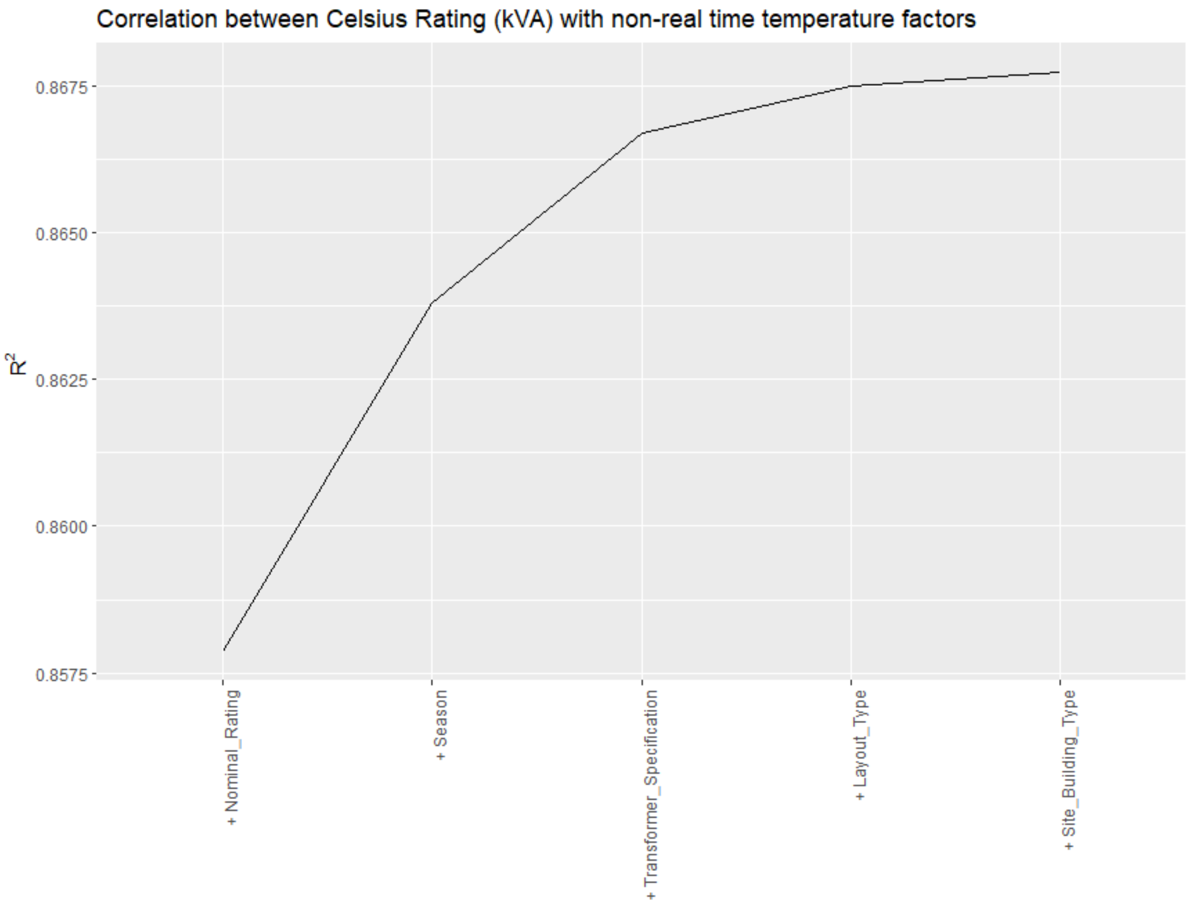

Figure 32: Correlation coefficient minus site age

The calculation for daily rating consists of a low and high value based on 95% confidence bounds. Linear correlation is used between the temperature factors and the transformers high and low value of daily rating to produce an equation in the following form:

$$R_{Cel} = C_{NR}R_{Nom} + F_{Season} + F_{Building\ Type} + F_{Spec} + F_{Layout} + \mathrm{C}$$

Where,

R_{Cel} is the Celsius rating in kVA

C_{NR} is the nominal rating coefficient

R_{Nom} is the nominal rating in kVA

F_{Season} is a number that depends on the season of the year

$F_{Building\ Type}$ is a number that depends on the building type

F_{Spec} is a number that depends on the transformer specification

F_{Layout} is a number that depends on the layout type

C is a constant

High and low values for each constant have been derived using the transformer's daily high and low rating value. The equation can be used to calculate the likely range for transformer rating by using high and low values given in the tables below. The values of the constants and coefficients also reveal the impact of the various factors on the calculated rating, and these comments are also included in the tables below. All variables in figure 32 interact with each other. If a value is negative it means it is decreasing the transformer's rating and hence it is negatively affecting its thermal performance. If it's positive the transformer's abilities have been increased.

Term	Description	Low	High	Comment
C_{NR}	Nominal Rating Coefficient	1.15	1.29	The range in these numbers is relatively narrow, indicating good certainty about the impact of nominal rating on the result.
C	Constant	60	88.3	The range of the constant is driven by the stochastic nature of the underlying data, creating more uncertainty in the result.

Table 12: Constants for Celsius rating (CR)

$T_{Building\ Type}$ (kVA) Building Type	Low	High	Comment
Stone/Brick	4.52	13.34	Building type has a significant impact on the daily rating, where the impact ranges from -5.89kVA to 13.34kVA. Stone/Brick sites have the highest ratings on average. One reason is these sites have working ventilation to cool the asset indoors, which will allow more thermal capacity to be obtained. These sites also have reasonable thermal mass and are not impacted significantly by solar gain. Fenced enclosure (which is used as the base level, and so is set to 0) has ratings somewhere in the middle, due to the natural cooling effects of being outside with good ventilation. However, some sites may be exposed to solar radiation. Substations that are part of a larger building have a negative effect on the daily rating. The reason for this is that the assets are not exposed to outdoor weather and solar radiation, and the ventilation is unlikely to be optimum due to physical constraints on the site. Metal kiosk and GRP sites have the biggest uncertainty in their ratings, suggesting that the sites are highly influenced by other factors, for example, if they are shaded or exposed to sunlight and weather conditions.
Fenced Enclosure	0	0	
Part of Larger Building	-9.58	-1.207	
Metal Kiosk	-1.24	3.715	
Glass Reinforced Plastic (GRP)	-5.89	8.293	

Table 13: Constants for building type

T_{Season} (kVA) Season	Low	High	Comment
Autumn	0	0	Season has some impact on the rating, ranging from -62.67 kVA to 37.59 kVA. As expected, ratings are higher in the winter, due to the increase in cooling from lower ambient temperatures and more precipitation. Conversely, ratings are lower in summer as the higher ambient means it is harder for heat to escape from the surface of assets. While both autumn (which is the base value and so set at 0) and spring are in between summer and winter, it is noted that
Spring	6.56	12.3	
Summer	-54.1	-62.67	

T_{Season} (kVA) Season	Low	High	Comment
Winter	34.3	37.59	Spring has the most uncertainty about the impact on the ratings, demonstrated by the range between high and low values. This may be a general feature of this season, or may be down to the particular year for which the trial ran.

Table 14: Constants for seasons

$T_{Transformer\ Spec}$ (kVA) Transformer Specification	Low	High	Comment
T1	36	50.83	Old style T1 transformers have the highest ratings on average, which is likely to be because they are often over-specified and designed to a larger safety margin Newer transformers have lower Celsius ratings on average.
ESI 35-1	0	0	

Table 15: Constants for transformer specification

$T_{Layout\ Type}$ (kVA) Layout Type	Low	High	Comment
Full Unit Substation	0	0	The transformer specification has a small impact on Celsius rating, ranging from -103.88kVA to 0kVA. Transformers which are separate to LV boards and RMU have lower daily ratings than full unit substations, which is not as expected, however, this 'layout' type interacts heavily with the Specification type described above and with building type, for example, GRP substations are often unit substations. Another possibility for the numbers produced is that full unit substations may have better ventilation, or the model is overestimating the daily rating for full units that have worse ventilation. Separate unit substations also have a bigger spread between low and high values. This is likely because the majority of the sites fall into this category, and therefore the most diversity is represented here. Where a site has two transformers, the heat of one transformer will be influenced by the heat coming from a second transformer, thus limiting its thermal capacity.
Separate Units	-10.2	-20.7	
Separate - two transformers	-96.16	-103.88	

Table 16: Constants for layout type

The obtained equation and temperature factor constants are used to calculate the Celsius Rating, which is a model of the transformer's daily rating. The accuracy of the equation derived for the Celsius rating is tested by investigating the difference between the model (Celsius rating) and the true value (daily rating), this is known as the residual and is plotted below. The lower bound of the transformer daily rating value is used.

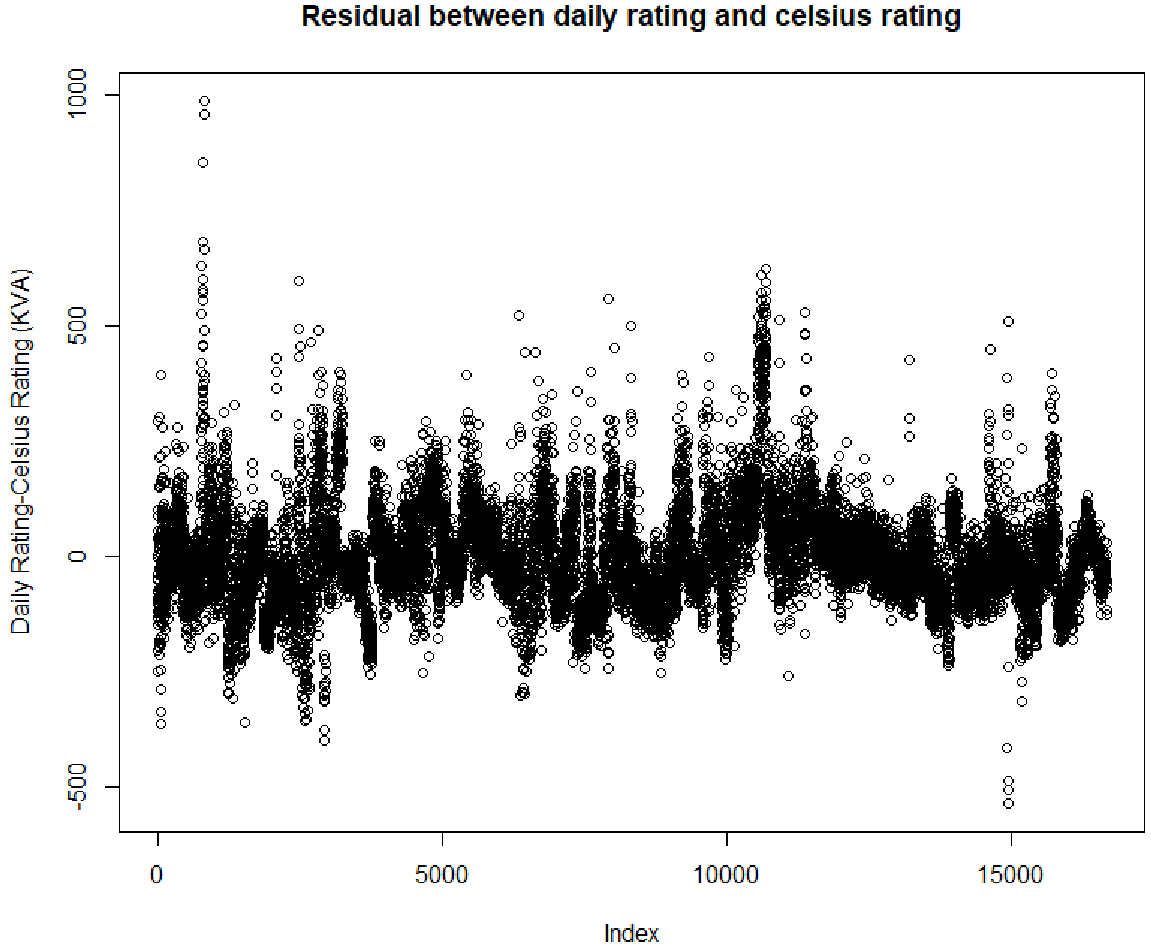

Figure 33: Residual of the CR and daily rating

The residual fluctuates around 0 for the different sites and statistical data for the graph can be seen below. The graph shows that 50% of the residual lies within the -67.6 to 55 kVA range, which suggests a good estimation of daily rating. However, there are significant outliers, so use of this model should be as a first estimate only, and if a more accurate informed rating be needed, then the daily rating should be calculated using measured temperatures.

4.3 Simplified Celsius Rating Equation

Figure 32 shows that Nominal Rating is by far the most impactful factor to determine the daily rating. A model including only this aspect gives an R^2 value of more than 0.85, which is already a good indicator. Therefore, a simplified model can be developed taking into account only nominal rating.

Figure 34 is a scatter plot showing the relationship between the daily rating of the transformer and it's nominal rating. The equation defining this relationship is seen below:

$$R_{Cel\ Simplified} = 1.1R_{Nom} + 112 \ \ (kVA)$$

Where $R_{Cel\ Simplified}$ is the simplified Celsius Rating which is a model of the transformer daily rating based on the nominal rating. The equation tells us that the Celsius rating of a transformer is on average 10% and an additional 112 kVA larger than the nominal rating. However, it can be seen in Figure 34 that while this equation can be used to give an indication of the likely rating, the calculated daily ratings show a significant range of results around this line. This highlights that the simplified Celsius equation should not be used as a basis for planning decisions in individual cases, and the daily rating should always be calculated.

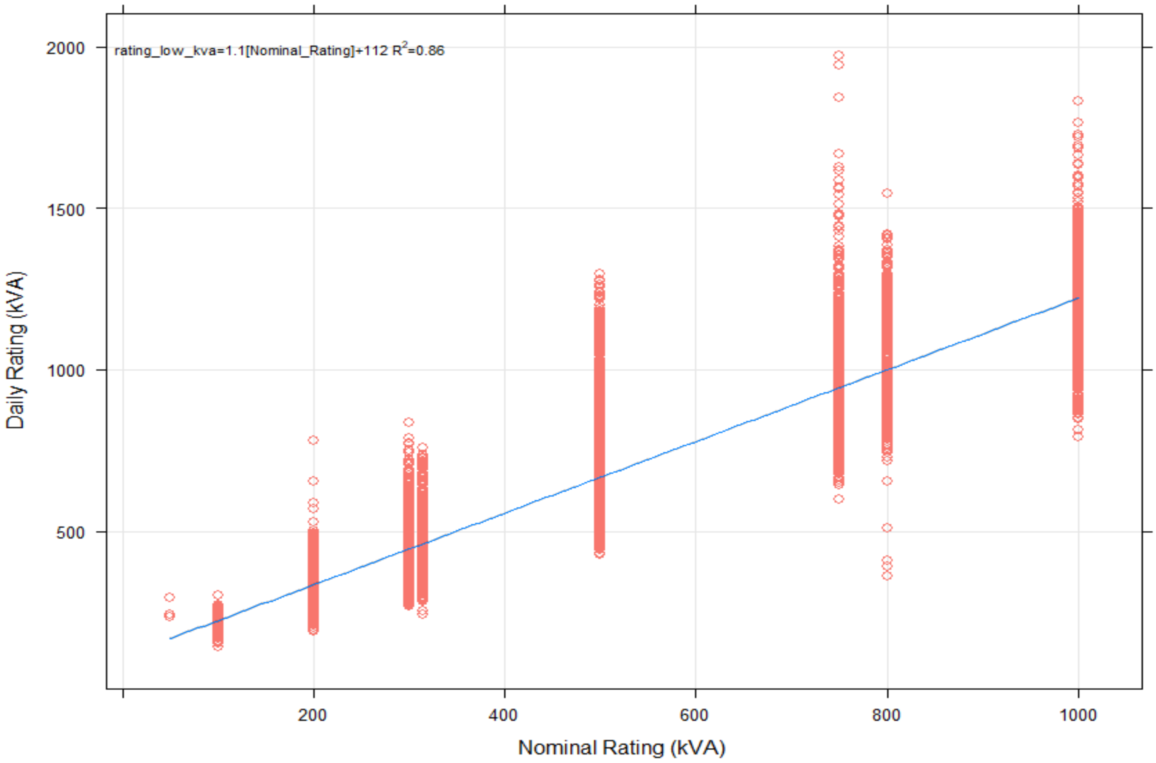

Figure 34: Linear correlation for daily rating and nominal rating

The accuracy of the equation derived for the simplified Celsius rating is tested by investigating the difference between the model (simplified Celsius rating) and the true value (daily rating). This residual is plotted below.

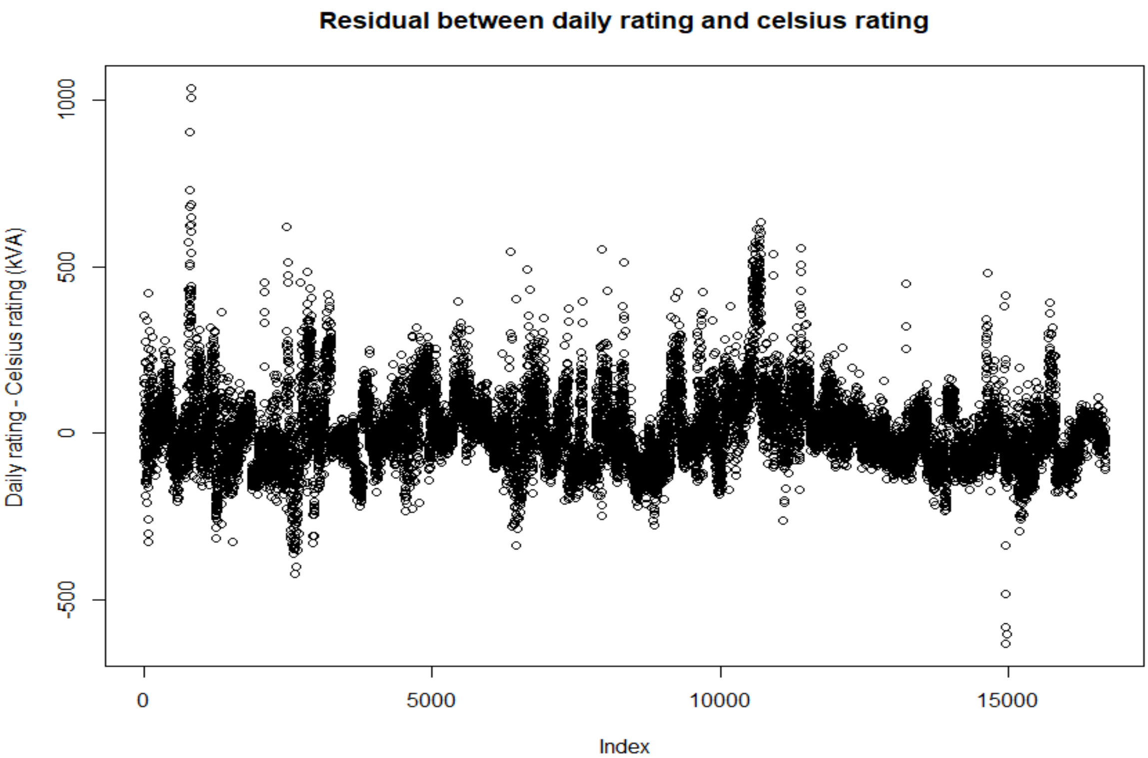

Figure 35: Residual of daily rating and CR based on nominal rating

The graph shows a range of residuals that fluctuate around 0. 50% of the data lies within the -67 to + 61.5 kVA range. The smaller the range and the closer the median is to the mean, the more accurate the model is.

As with the full Celsius rating equation, there are significant outliers in this graph. Notably, this method will not take into account the impact of the other temperature factors, including building type which was found to have a significant impact on rating, and specification type, which is notable due to the findings of the Daily Rating Study that found that unit transformers are most likely to have unusually low daily ratings. For these reasons, the use of this model should be as a first estimate only.

5. Conclusion

In this deliverable, three methods of estimating a more informed transformer rating were developed and presented:

- **Transformer Daily Rating** is determined from estimated hotspot temperature and measured transformer load, and by comparing this with the maximum temperature at which a transformer can operate without accelerated wear and aging. The daily rating is then compared to the more conservative nominal rating. The estimated hotspot temperature is determined using the methodology developed in the Transformer Hotspot Study, and is based on surface and ambient temperatures and transformer specification.
- **Celsius Rating** is based on the set of temperature factors that are easily accessible, without the need for real time data. This includes 'season' as a factor, so while it is not a real time rating, it does change over the year.
- **Simplified Celsius Rating**, which is based on only nominal rating of the transformer, and is a high-level indication of the likely capacity of the transformer for the cases where there is not all of the other information.

The Celsius Rating and Simplified Celsius Rating were developed by building a model of the Daily Rating using the various temperature factors. All of this analysis is built on the hotspot temperature estimation methodology, which has a few limitations that should be noted for context:

- **Inadequate smart transformer data** –There is only one smart transformer which has produced consistent, high quality data, and two more have been loaded to produce data samples which are limited in volume but were used for validation.
- **Limitations to the selection of internal monitoring transformers** – Due to safety and practical reasons, it was not possible to include outdoor substations or full unit Glass Reinforced Plastic enclosed substations in the selection of sites with internal oil monitoring, and only one unit transformer was included.

The result is that while it is possible to make reasonable assumptions about the application of the findings to the wider substation group, some of these applications are not tested. However, the insight developed during this analysis is extensive, and can be applied with appropriate margins of safety.

Further investigation into the results of the Daily Rating Study revealed that there are cases where the daily rating falls below nominal rating – meaning that the estimated hotspot temperature is higher than expected for the load, and that the capacity of this transformer in this environment is less than the nominal rating suggests. There are only three examples of sites where this is happening persistently (either continually or seasonally). This variation is not likely to be fully represented in the Celsius rating, and will not be recognised in the Simplified Celsius Rating, and so care is recommended when using these two models, particularly for unit transformers.

Other sites showed exceptionally high calculated daily rating for individual days, while the rest of the time the results were much more in line with other sites. This highlights the need to take into account data across multiple days, over a sustained period of time, to gain a balanced view of the rating. A single day of data may produce misleading results.

The Celsius and Simplified Celsius Ratings can be used to give an indication of the likely rating for a site with set characteristics, the calculated Daily Ratings for a given site may range significantly from this result. This highlights that the Celsius and Simplified Celsius Rating should not be used as a basis for planning decisions in individual cases, and the daily rating should always be calculated.

5.1 Next Steps

The next steps within the Celsius project are to develop a Thermal Rating Tool that will make all findings of this deliverable accessible. The tool will include all three of the Ratings methods listed above and allow users to input data and information about the transformer and the site and output a more informed rating for the transformer. The later phases of the Celsius project will further develop this tool to include recommendations for appropriate cooling technologies and develop it into a useful and valuable Business as Usual tool.

As mentioned previously, future work could be undertaking to improve the results produced so far in phase 1 of the project. The hotspot study investigation could be updated in the future if heavier loaded smart transformer data can be collected, preferably from a wider range of sites. Including outdoor and glass reinforced plastic sites with internal monitoring would also be of benefit. This would enable further refinement and validation of the hotspot calculation work. Further information and data regarding temperature factors could be incorporated into the Temperature Factors study, which would enable further investigation of relevant factors that influence asset performance.

Phase 1 of Celsius, and the development of the tool described above, has been undertaken in such a way to allow for updates due to identification of additional information and data possible. However, this future work for phase 1 is out of the scope of the Celsius project.

6. References

[1] "Part 7 Loading Guide for Oil-Immersed Power Transformers," 2009 .

[2] E. N. West, "Transformer Ratings," 2009.