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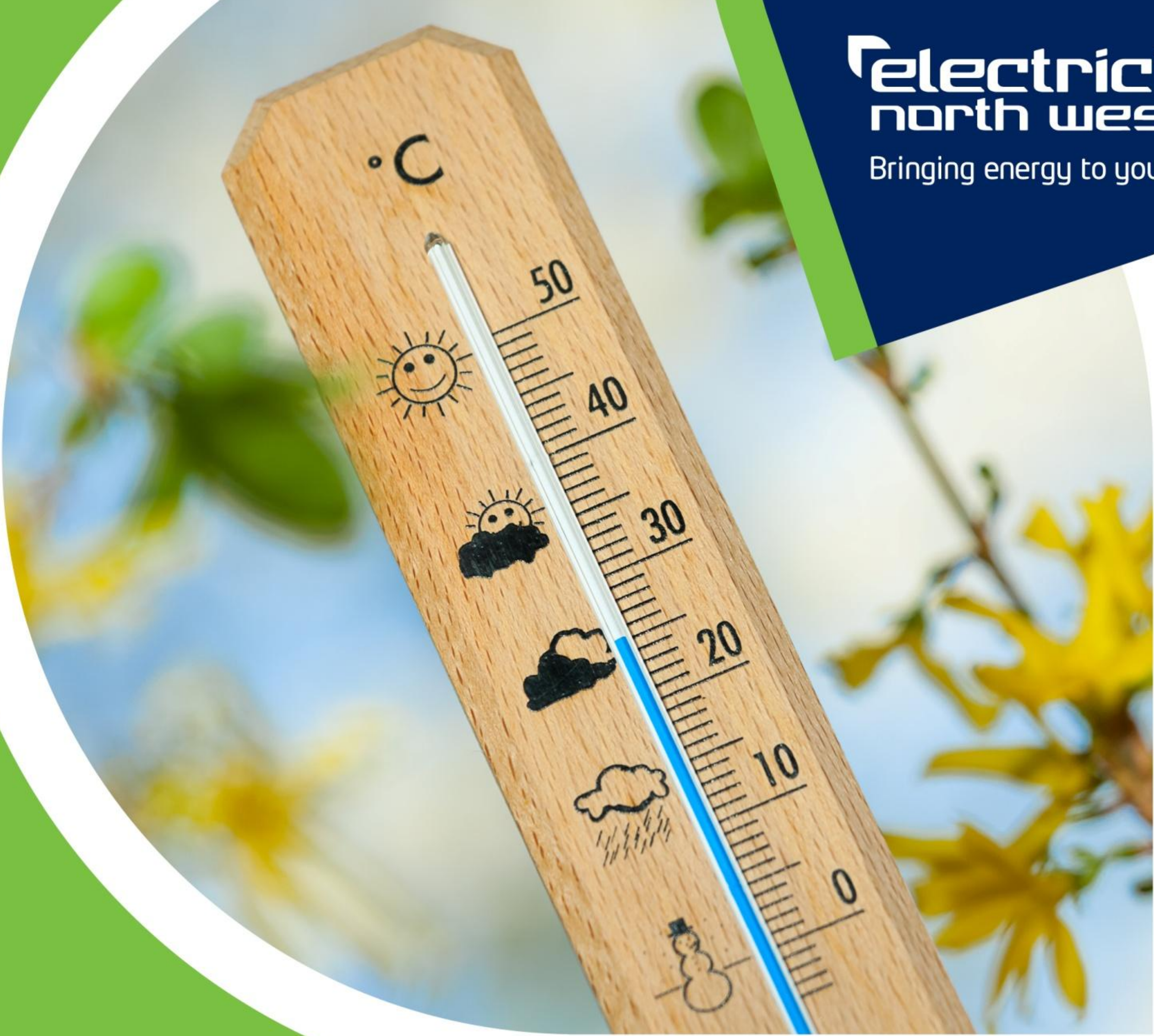

Celsius

Electricity North West’s approach to managing thermal constraints at distribution substations

31 March 2020

VERSION HISTORY

Version	Date	Author	Status	Comments
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CONTENTS

GLOSSARY OF TERMS

Term	Description
Active cooling	Cooling provided by actively controlled means eg fans.
Ambient temperature	Temperature of the air surrounding a component
BAU	Business as usual
Cable	An underground conductor used to distribute electrical power, installed directly in the ground or in ducts or troughs
Capacity	The amount of power that can be delivered by an asset
CBA	Cost benefit analysis
CNAIM	Common Network Asset Indices Methodology
Current	The flow of electricity through a cable, measured in amperes
Demand	The amount of electrical energy that is being consumed at any given time
Distribution substation	A substation which usually contains high voltage (HV) switchgear, an HV/LV transformer, LV switchgear and short length of LV cable(s) and can be either pole- or ground-mounted
ENA	Energy Networks Association
GB	Great Britain
GRP	Glass reinforced plastic
High voltage (HV)	Voltages over 1kV
Hot spot temperature	The peak temperature reached at a position in a transformer winding which determines the maximum load the transformer can carry
LCT	Low carbon technology
NIC	Network Innovation Competition
Passive cooling	Cooling provided by non-controlled means eg reflective paint, shading from sunlight
SDRC	Successful delivery reward criteria
Thermal coefficient	The constant by which the external temperature needs to be multiplied to ascertain the hot spot temperature
Thermal constraint	The restriction of an electrical asset’s capacity due to the operating temperature
Thermal headroom	The amount of capacity available for use
Thermal Ratings Tool	Software/Microsoft Excel-based solution to calculate the available capacity at a site, based on inputs of temperature, substation environment and asset type

1 INTRODUCTION

1.1 Purpose of document

The purpose of this document is to fulfil the requirement associated with the Celsius successful delivery reward criteria (SDRC) CI.2 – Publish Electricity North West's approach to managing thermal constraints at distribution substations.

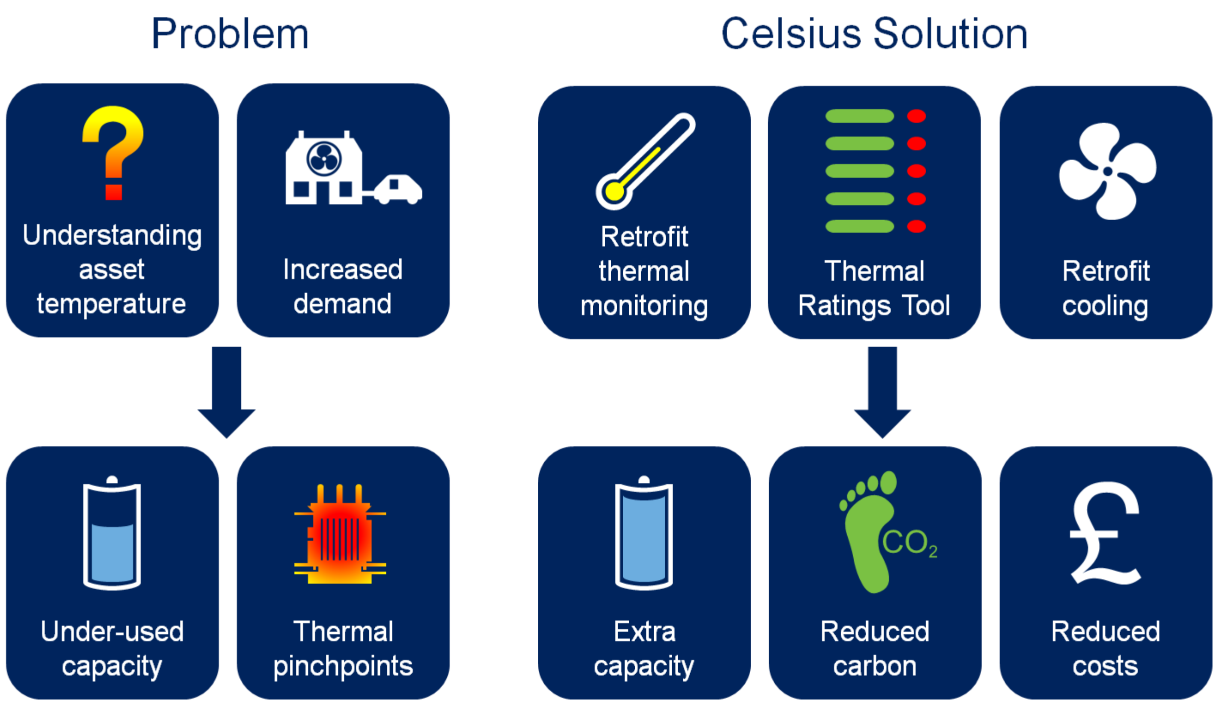
The aim of this document is to outline Electricity North West's approach to managing thermal constraints at distribution substations, incorporating the outcomes of the Celsius project.

1.2 Background on the Celsius project

Celsius is funded via Ofgem's Network Innovation Competition (NIC) funding mechanism. The project was authorised to commence in December 2015 and will complete in March 2020.

Celsius explored innovative, cost-effective approaches to managing potentially excessive temperatures at distribution substations, which could otherwise constrain the connection of low carbon technologies (LCTs).

Figure 1: Problem and solution illustration



Celsius identified potential thermal issues by establishing how different distribution substations behave thermally under a variety of load and environmental conditions. Celsius produced a more informed rating to better understand the real thermal ratings of distribution substation assets to unlock capacity using:

- **Retrofit thermal monitoring**: By measuring asset and ambient temperatures, and relating these to a range of environmental, load and seasonal factors, Celsius enabled understanding of the real thermal ratings of assets, rather than the nominal ratings that are used today. This allowed improved understanding of the amount of latent capacity which could be accessed without further intervention.

- **Thermal Ratings Tool**: the learning from the retrofit thermal monitoring trials and analysis was transferred into a simple tool that can be used by operations and planning employees, to better understand the capacity of the existing or planned network.

Celsius identified, evaluated and demonstrated a range of retrofit cooling technologies that can be used to directly manage the temperature of assets. By managing temperature in this way, Celsius delivered additional capacity release. Customer surveys established customer perception of retrofit cooling techniques and whether the application of these techniques is as acceptable to them as traditional reinforcement.

2 EXISTING POLICY

ENA Engineering Recommendation P15, Transformer Loading Guide, is a key GB power sector standard for the loading of transformers. However, this standard largely focuses on emergency ratings rather than the ratings during normal operation. Additionally, the document was published in 1971, and as such, the ENA have classed it as 'no longer maintained'.

The nameplate rating of distribution transformers is commonly used for the purposes of operation and planning. The learning from Celsius shows that this is a conservative assumption, with the thermal performance of transformers varying significantly between sites. In the majority of cases transformers are able to carry more than the nameplate rated load before reaching their design temperatures.

Additionally, while transformer and substation cooling solutions are used in distribution substations in rare occasions, it is not standard practice to alter the transformer rating to reflect this change to its operational environment. Learning from Celsius indicates that the effective thermal rating of a transformer can change with the implementation of improvements to its surrounding environment.

3 CELSIUS LEARNING

Trials carried out as part of the Celsius project have generated significant learning which is expected to drive policy changes and inform new methods to release capacity in existing distribution network equipment, supporting the connection of low carbon technologies.

The calculation of more informed ratings for distribution transformers at the Celsius trial sites showed that it is possible to release an average of 30% on top of the nominal ratings. In some cases, the more informed rating was lower than the nominal rating, which can be used to inform intervention measures where needed. It is expected that a significant proportion of substations could be supported by Celsius; the method is suitable for any ground mounted transformer with a nominal rating of 300kVA or above. The more informed rating approach required the installation of sensors to measure ambient and transformer temperature, voltage and current, and access to weather data for outdoor sites.

Learning from the Celsius retrofit cooling trials suggests that the more informed rating of a transformer can be further improved with the installation of active cooling technologies, such as fans, or improvements to the passive cooling arrangements, eg better ventilation.

Celsius carried out extensive customer engagement to test the customer acceptance of the solutions. This found that 89% of all trial survey respondents found the retrofit cooling technique installed at their nearest substation acceptable, with only 15% noticing a change to their nearby substation. There were a small number of customer complaints about the noise of active cooling technologies, and learning was made about how this could be mitigated by a change of design or a change of the fan settings.

The University of Southampton carried out an asset health study, to determine if the methods trialled by Celsius have any impact on asset life. It concluded that although the use of more informed ratings that are higher than the nominal rating is likely to lead to an increase in operating temperatures, remaining within the design thermal limits should ensure that the rate of thermal degradation does not shorten the life of the transformer.

The methods developed and trialled in the Celsius project are described in the sections below.

3.1 More informed rating for ground mounted transformers

The project developed a methodology for determining a more informed rating for a transformer by using:

- Ambient temperature in the substation measured at high level (approximately head height) and away from sources of heat or ventilation
- Transformer surface temperature at top oil level, measured on the surface of the tank (as opposed to any cooling fins or radiator pipes)
- Three phase power.

This data is measured at half hourly frequency and transmitted or collected frequently (eg once per day). The site should be monitored on an ongoing basis to manage any change to the more informed rating, and to mitigate risk.

The temperatures are used to calculate the internal hotspot temperature; this calculation is dependent on the transformer specification.

Once the hotspot temperature has been estimated, the next step is to build a model for the calculated hotspot temperature based on transformer load and measured environment data.

Within the project, it was determined that the model should take the form of:

$$\text{For indoor transformers: } T_{hs} = \boldsymbol{a}\, S^2 + \boldsymbol{b}\, T_{amb} + \boldsymbol{c}$$

$$\text{For outdoor transformers: } T_{hs} = \boldsymbol{d}\, S^2 + \boldsymbol{e}\, T_{weather} + \boldsymbol{f}\, W + \boldsymbol{g}$$

Where T_{hs} is the hotspot temperature, S^2 is the square of the apparent power in the transformer (total for all three phases), T_{amb} is the measured ambient temperature in the substation, $T_{weather}$ is the temperature as reported by local weather stations, and W is the wind speed as measured by local weather stations. The coefficient terms ***a***, ***b***, ***c***, ***d***, ***e***, ***f***, and ***g*** are determined by building linear regression models from the data collected.

This model is best developed using a full year's worth of data, to take into account daily, weekly and seasonal variations. However, an initial estimate can be produced from less data, down to two weeks' worth of data, though the results should be used with caution.

This model can then be used to estimate the load at which temperature will reach the maximum allowed operating temperature, for given 'worst case' ambient conditions.

The resulting value of S is the more informed rating in apparent power. It is recommended that in practical applications this rating should be restricted to a maximum of 150% of the nameplate rating while further confidence in the methods is being built up.

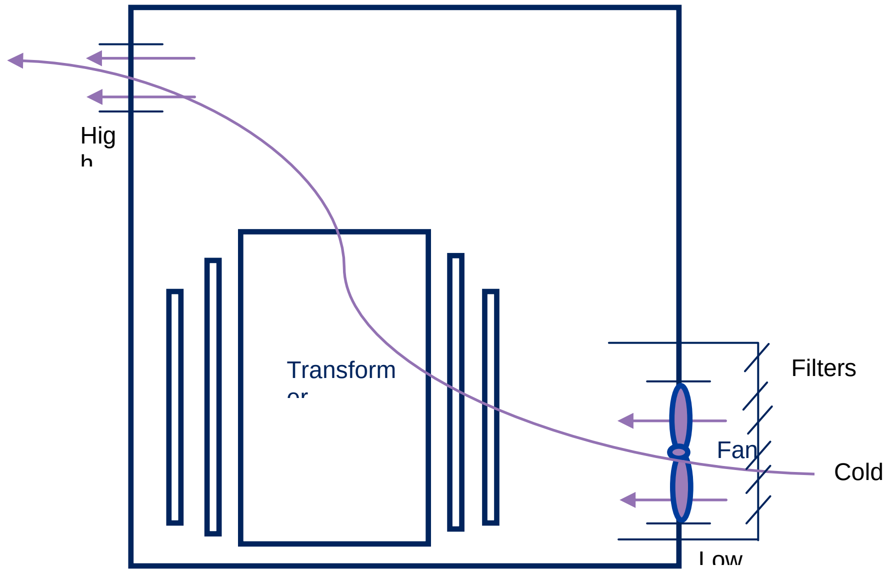
The more informed rating can be lower than the nameplate nominal rating of the transformer, as well as higher. However, in the Celsius trial, these cases were rare, and on average the more informed rating was approximately 130% of the nameplate rating across the trial.

3.2 Retrofit cooling technologies and techniques for ground mounted transformers

The following methods were trialled in the Celsius project:

- **Altered passive ventilation** – this involved alteration to the arrangement of vents. Substation size, layout, and material can vary widely, and there is therefore unlikely to be a suitable single standard approach that will fit them all
- **Forced ventilation (positive)** – fans are used to push air in through a low vent, which then passes over the substation equipment and escapes through a high vent.

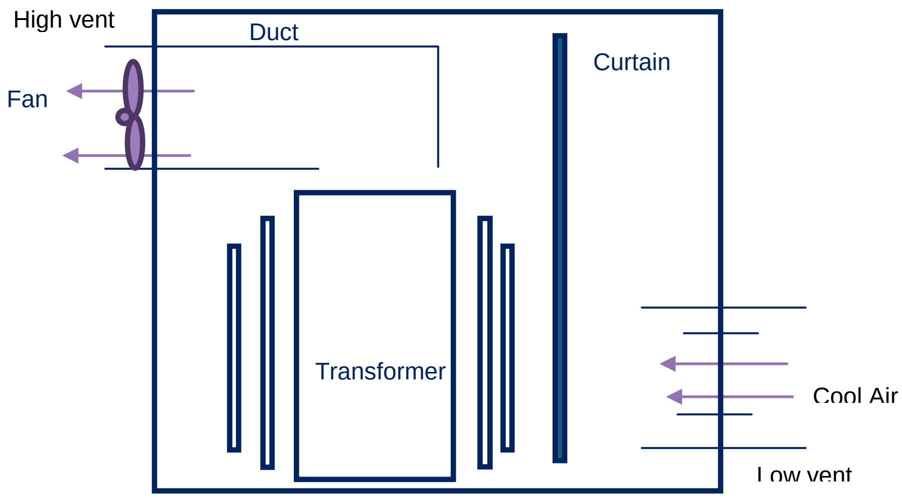
Figure 2: Illustration layout of the positive forced ventilation technology



  - This technology works by using the fan to draw cooler air from outside into the substation through vents situated low down in the substation. There is also a high-level vent placed so that it naturally draws the cooler air over the transformer, thus cooling it down.
  - The active cooling fan is sensitive to the temperature of the transformer and can be set to only operate when the temperature increases beyond a set point. This means that energy requirements can be minimised.

- **Forced ventilation (negative)** – Fans, curtains and ducting are used to direct and pull air over the substation equipment and out through a high vent. Cooler air is naturally drawn in through low vents.

Figure 3: Illustration layout of the negative forced ventilation technology



- **Protecting outdoor transformers from solar radiation** – Two techniques were trialled to protect outdoor transformers from solar radiation.

  - White paint – white paint was applied to transformers in outdoor sites to reflect solar radiation and to protect equipment from solar heating.
  - Solar shade – the solar shade includes a substantial aluminium structure on which a canvas shade is mounted. The canvas includes venting holes to allow hot air to escape. The structure is designed to be a permanent outdoor structure, withstanding adverse weather conditions.

The most effective cooling solution was the positive pressure active cooling solution, which released on average 12% of nameplate rating, and in some cases increased the Celsius rating by more than 30% of nameplate rating.

The passive ventilation approach showed that in some cases, significant capacity can be released through this method, releasing 10% or more of nameplate rating. However, in other cases, little or no improvement was found. It is recommended that this method is only used where the existing arrangements are inadequate. Guidance is needed on how to assess the current ventilation performance.

The two technologies trialled with the aim of protecting outdoor transformers from solar heating provided mixed results, with little consistent evidence of an improvement.

3.3 Pole mounted transformers and cables

Pole mounted transformers were included in the retrofit monitoring trial, and monitoring equipment was installed to monitor the load, surface and ambient temperatures. While some overarching conclusions were made, it was not possible to develop a model for calculating hotspot temperature of these transformers, and therefore a more informed rating methodology could not be developed. It was decided that cooling technologies were not suitable for the retrofit cooling trial, due to safety and logistical issues, and there would be only marginal improvement to the rating of an asset.

The retrofit monitoring trial included monitoring the surface temperature and load of LV way cables at 22 sites, totalling approximately 100 cables across these sites. This includes cables in open air ducts and buried in sand. Data collected including loading and surface temperature of the cables, ambient temperatures in the cable environment, and information about cable arrangements. However, it was not possible to develop a model for calculating core temperature of these cables, and therefore a more informed rating methodology could not be developed. The Celsius retrofit cooling trial included the use of a different backfill material, which seemed to improve the heat transfer away from the surface of the cable, resulting in a lower cable surface temperature. However, as a cable rating method could not be determined, this could not be translated into an improvement in rating.

4 PROPOSALS FOR NEW POLICY

The Celsius methods can be rolled out across networks gradually as suitable substations are identified with loading or thermal issues. The frequency with which these issues arise is likely to increase with increasing uptake of low carbon technologies, but benefits can also be realised today.

In the business as usual (BAU) process, sites which have:

- loading or thermal issues
- ground mounted transformers
- a nominal rating of 300kVA or above

can be identified as suitable for Celsius. These sites will have additional monitoring installed and be referred to as ‘Celsius sites’.

Note: Celsius should only be considered when there are no time constraints around the intervention (eg in a connections request). However, if the Celsius monitoring data already exists it can be used to support the planning study.

Celsius monitoring consists of:

- Transformer surface temperature measured at the top oil level
- Transformer demand measured through three phase current and voltage sensors
- For indoor sites: ambient temperature measured away from the transformer or other heat or ventilation sources
- For outdoor sites: weather data, including temperature and wind speed is preferred to local ambient monitoring due to the difficulties in achieving a consistent ambient temperature measurement in an outdoor setting.

The monitoring data will allow the calculation of the more informed or ‘Celsius rating’. The Celsius rating can be used in planning, asset management, network capacity and connections decisions, to enable the support of greater load growth without the need for network reinforcement.

The measured temperature and load data can also be used directly, for example to improve network modelling and to inform connections decisions.

The Celsius rating and data will be used in the CNAIM model, allowing a more accurate indication of asset health and risk potentially lowering the number of sites being referred for intervention.

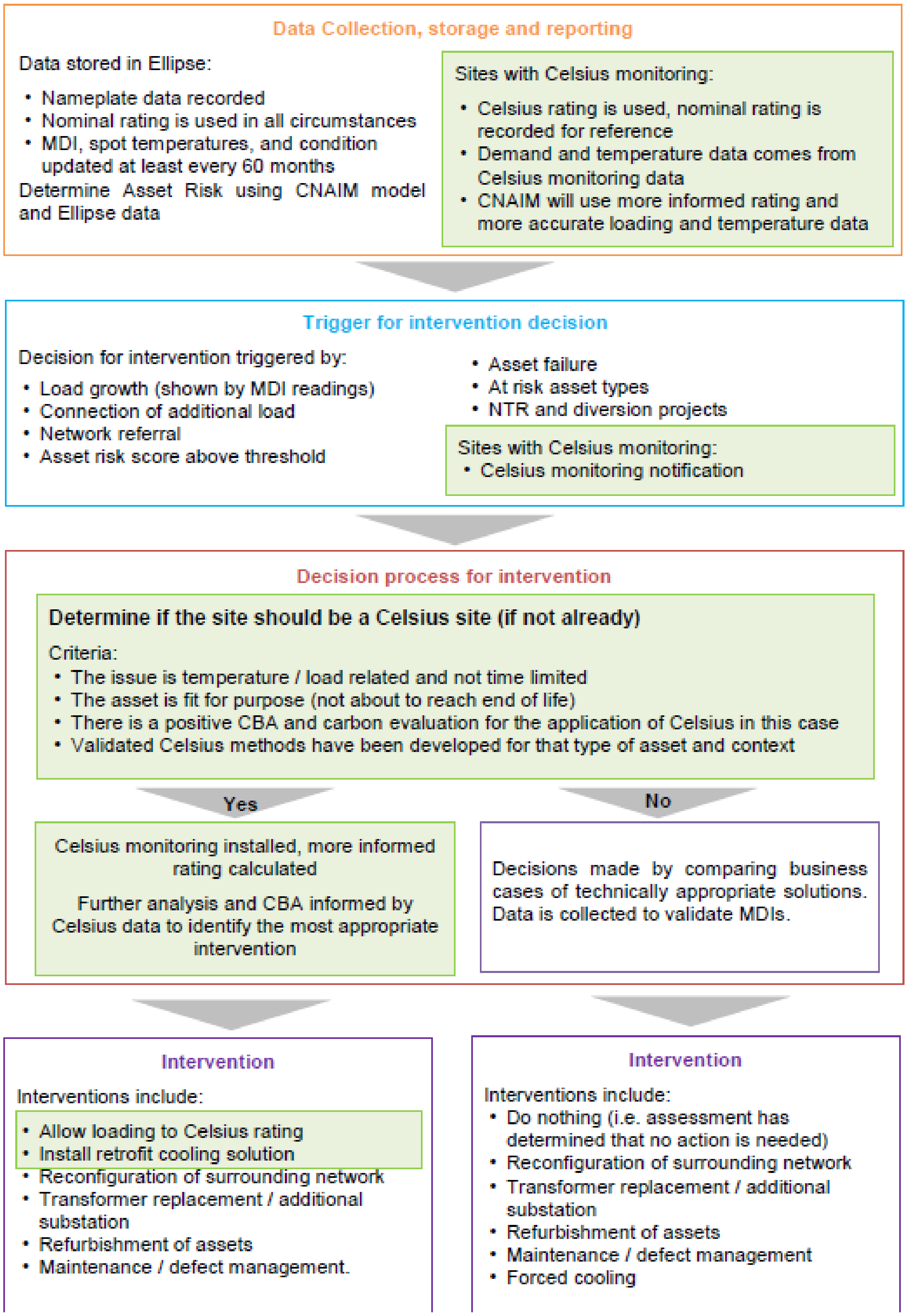
The data can be used to produce notifications to warn of any issues developing over time, eg unexpected temperature rise. These notifications will be carefully tuned to support timely reaction to warning signs of failure, without over-triggering. It is envisaged that the notification will be sent as an email or SMS to key members of Electricity North West and will indicate if the site needs visiting urgently.

The Celsius monitoring data can be used to enable optimised selection of interventions and to monitor resulting benefits. Interventions can include but are not limited to:

- Retrofit cooling technologies
- Demand side response
- Network meshing
- Network reconfiguration
- Traditional reinforcement.

Figure 4 summarises the new asset management process which incorporates the outputs from the Celsius project. It shows all of the elements in the current process, with the new processes highlighted in the green boxes.

Figure 4 Celsius incorporated into current process



When a non-Celsius site is flagged for an intervention, the first step is to decide if it is economic to deploy Celsius monitoring. It is expected that the cost benefit analysis (CBA) will be positive in most situations. This is because Celsius monitoring is easily deployable and low cost once the procurement, communications and IT integration is established.

As in today's process, the maintenance team will decide what, if any, intervention is required including installing Celsius monitoring. As the decision for intervention becomes more complex, it is expected that the decision process will have to develop as well. It is envisaged that there will be standard CBAs and carbon cases that can be easily applied to common situations, enabling quick decisions and minimising any additional workload.

After Celsius monitoring has been installed for a period, an initial assessment of the Celsius rating can be made which can be updated as more data is collected. This will determine the potential capacity which can be released and allow assessment of the interventions.

The asset database shall record the Celsius rating so that colleagues are aware that the substation has a modified rating. Labelling shall be deployed on site to highlight that the nameplate rating has been modified and refer colleagues to the asset database for the Celsius rating.

The Celsius methods should not allow a transformer to operate beyond its design temperature but as this is a new way of operating a transformer the probability of failure needs to be carefully considered. It is likely that the risk of failure will be reduced because of the monitoring and the notifications will be tuned to support timely reaction to warning signs of failure. Post-mortems shall be carried out on failed equipment at Celsius sites and compared with non-Celsius equipment and, if necessary, the Celsius process should be updated.

There are some potential gaps in the range of sites covered by the work to date, eg outdoor or GRP substations and transformers with a nominal rating 200kVA or below. Further work is required to develop methods for these categories of sites, but insight can be gained from deploying the monitoring even at these sites.