Passive Cooling Technology Recommendations

Passive cooling technology assessment including research and test, recommendations for including in the Celsius retrofit cooling trial, and initial site selection.

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Report for Electricity North West

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1 Introduction

1.1 Celsius

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

The first phase of Celsius involved a retrofit monitoring trial of 520 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 monitoring equipment is being provided by Ash Wireless, and is described in a series of separate documents. A mobile application has been developed which supports the installation of the equipment and enables recording of key installation and site data. There is also a data management system which receives data remotely from the monitoring equipment, and processes, stores, and provides access to it. The installation app and data management system were both developed by Ricardo Energy & Environment.

The data from these sites is being used to develop an understanding of the thermal behaviour of the substation assets in different locations and environments, and therefore develop a methodology for estimating a more appropriate thermal rating for these assets.

The second phase of Celsius will involve trialling a range of retrofit cooling technologies in a subset of these substations. The intention will be that these cooling technologies will enable the assets to carry more load before exceeding recommended operating temperatures, enabling the calculated rating to be raised higher.

1.2 Purpose of this document

Ricardo Energy & Environment were asked to carry out research and testing for a number of retrofit cooling technologies, focusing on the passive approaches (as opposed active cooling with fans or pumps). These technologies included:

- Colour change of assets and substations
- Pole mounted transformer shading
- Ground mounted transformer or substation shading
- Improved ventilation of substations

Ricardo are also investigating the use of alternative backfill materials for cables, which will be reported separately. It is intended that Electricity North West will also provide their own insight and experience on their physical assets and installation procedures to make final decisions about the inclusion of these technologies within the trial.

The purpose of this document is to present the advice and recommendations from Ricardo Energy & Environment to Electricity North West on the suitability of the retrofit cooling technologies listed above for inclusion in the Celsius trials. This includes listing potential benefits, limitations, procurement options, and recommendations. The document also includes a site selection for the demonstration trial sites for those technologies recommended for inclusion.

This includes:

- **Section 2: Technology Investigation: Colour change of assets and substations** – A description of research and testing of the impact of changing the colour of assets, including test apparatus, methodologies, results, and recommendations.
- **Section 3: Technology Investigation: Pole mounted transformer shade** – A description of testing of the effectiveness of pole mounted transformer shades using the same apparatus as the colour shades, including test methodologies, results, and recommendations.
- **Section 4: Technology Investigation: Ground mounted shade** – Reporting the results of research and investigation, including requirements, limitations, characteristics and suppliers.
- **Section 5: Technology Investigation: Improved substation ventilation**– Reporting the results of research and investigation, including requirements, limitations, and approach.
- **Section 6: Passive Cooling Technology Site Selection** – site selection methodology and results

2 Technology Investigation: Colour change of assets and substations

2.1 Testing focus and overview

This technology is the simple concept of painting assets to change how they give off or absorb heat.

A number of paint colours have been tested using the test rig described in section 3, including white, black, and various grey shades, to compare their benefits when exposed to sunlight, and indoors. While the test rigs are designed to be representative of pole mounted transformers, the intention is to apply the knowledge at a generic level to ground mounted substations as well.

Two colour change approaches were investigated;

- **Light paint colours to reflect solar radiation** – solar reflective paint for assets that are in direct sunlight and are being heated significantly.
- **Dark paint that increases the emissivity of the surface** – to increase emission of heat from the surface so that asset heat can escape more easily.

A key advantage of the use of paint as a cooling approach is that it is a low-cost method which is potentially simple to implement, particularly in ground mounted assets. However, it was unclear what the benefits might be. A test bed was set up to test the effectiveness of changing the colour of substation assets as a method of keeping them cool. The aim of this activity was to test several paint colours; some selected to reflect solar radiation, and some to increase emissivity of the transformer surface enabling heat to escape more efficiently. The test bed was developed to be representative of pole mounted transformers, but it was assessed that the learning could be applied to any substation asset.

Initial research was carried out to determine beneficial colours to trial, and this indicated that a black surface may absorb more than three times the solar radiation than a white surface, indicating that white would be a good choice for outdoor assets exposed to sunlight. However, keeping assets white is impractical, particularly if they are not attended regularly, as with distribution substations.

Conversely, our research suggests that matt black paint is more beneficial within indoor substations, where the heat transfer from the asset can be increased by increasing the surface emissivity, but there is little or no direct sunlight.

The same test equipment was also used for the trial of pole mounted transformer shades.

2.1.1 Overview of test equipment

The test apparatus is shown in the photographs below.

Figure 1: Test rig with lids off (left) and inside view (right)

The test apparatus included 4 metal boxes (three for the colour trials, and one set aside for the shade trails described later), with a heating element inside. A concrete block was formed, and installed in the boxes supported off the bottom surface, to fill a significant proportion of the box volume while allowing fluid to circulate. The heating element fitted inside the concreate block, and the reservoir in the top was then filled with stones. Note that the images above show only one of two heating elements that was used; on each side. The fluid used was transformer oil.

This set-up is considered representative enough of a transformer for the purposes of the testing, with the validation of the testing being through comparison between the test rigs. KeLVN monitoring equipment was installed in order to gather data from the test rigs. This is the same equipment as is used in the Celsius trials. For each test rig, monitoring included:

- two internal sensors at the top and bottom oil level (temperature flying leads),
- two externals sensors located adjacent to the internal monitoring positions on their surface (single temperature sensors) and
- a temperature sensor on the lid of the box (single temperature sensor)

These sensors are shown in the image below.

Figure 2: Test rig with KeLVN sensors installed.

There were also two ambient temperature sensors; one positioned to receive direct sunlight, and the other in the shade. Weather data was recorded adjacent to the test rig through a small weather station, and using a light monitor to capture solar radiation.

The test apparatus was validated to ensure that each box behaved in the same way while being heated and being exposed to weather conditions. This took place over several weeks, while the heating elements in each box was operated at a matching load, and validating that the temperature readings were equal, within an acceptable margin of error.

This was initially carried using water instead of the transformer oil, to allow ease of making alterations, and to ensure that the apparatus was free from leaks. Over the period of validation, discrepancies in the measurements were discovered, and alterations made to the apparatus in response, such as altering positioning of the sensors, and ensuring the water levels were similar across the transformers.

The graphs below show data from the validated apparatus, taken from the internal and external temperature measurements of each tank. The status of the heating element is also shown; the heaters were turned on between 08:30 and 18:00 every day.

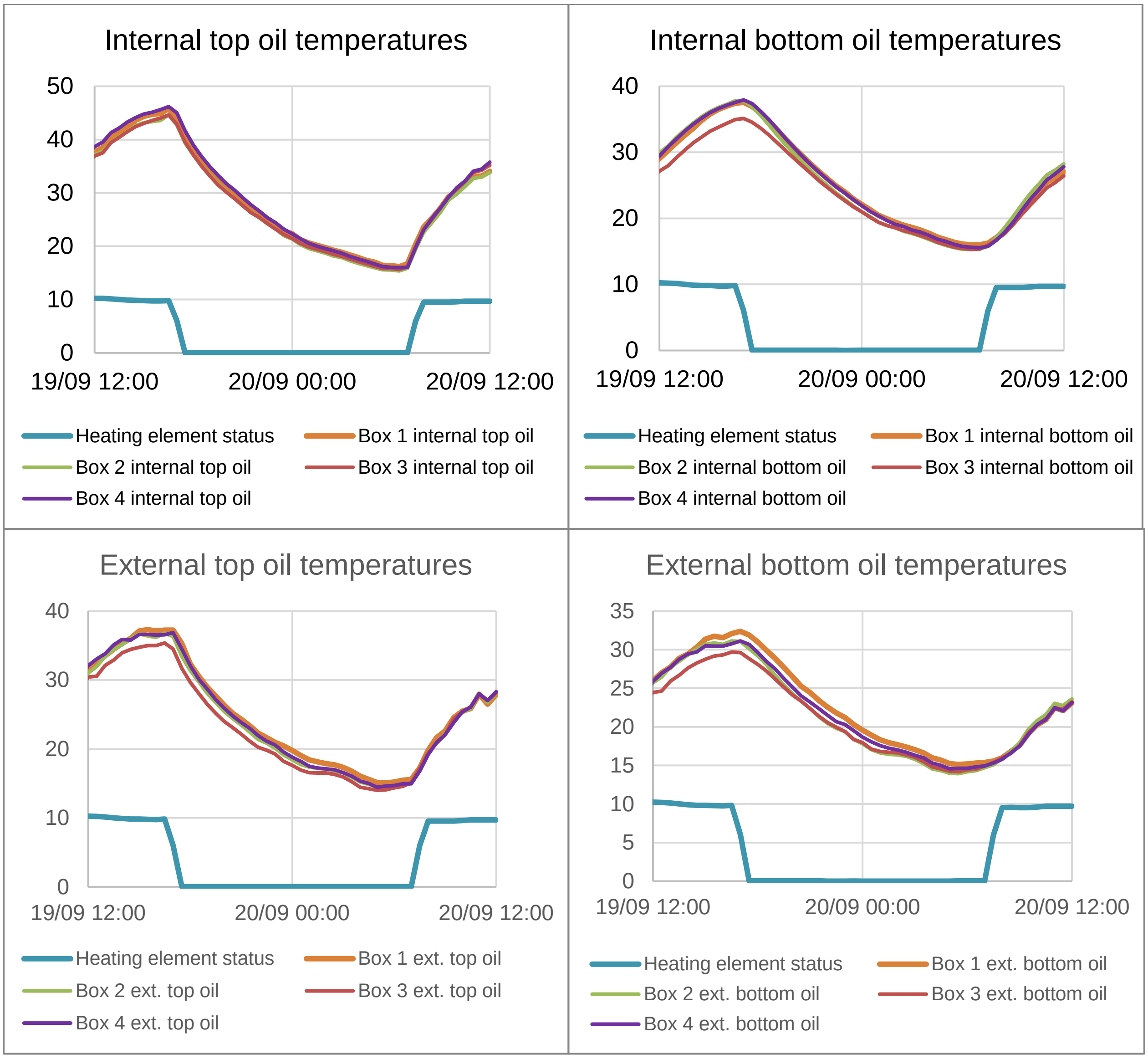

Figure 3: Validation of Apparatus - comparing data from each of the 4 boxes for internal top oil temperature (top left), internal bottom oil temperature (top left), external top oil temperature (bottom left) and external bottom oil temperature (bottom right). All graphs show temperature in °C.

The graphs show good agreement over the four boxes, with the average difference between the minimum and maximum reading of less than 2 degrees Celsius in each case, and the maximum difference never being more than 4 degrees.

There is some difference in environmental conditions between the boxes; the boxes are oriented such that boxes 3 and 4 both have the south facing side (a short side, with the longer sides facing east and west) exposed to radiation, and box 1 and 2 are shaded by the other boxes.

It was determined that this apparatus set-up is validated for use in the planned trials. Differences in behaviours must be viewed in the context of the results of this validation on the 19th and 20th October 2017.

The water was then replaced with transformer oil in each box. The graph below compares the internal top oil temperatures as each box was changed from water to oil. The time that each box was changed is marked.

The graph below shows that the temperature when filled with oil is much higher than that when water-filled. For the period when only boxes 3 and 4 are oil filled (23/09 – 26/09), they are more than 10 degrees higher temperature in the day than the water filled boxes 1 and 2.

The graph also shows that once all of the boxes are filled with oil, their thermal behaviour is very similar. Note that the shade testing had already begun at this stage, and therefore the impact of this is causing a wider spread of results.

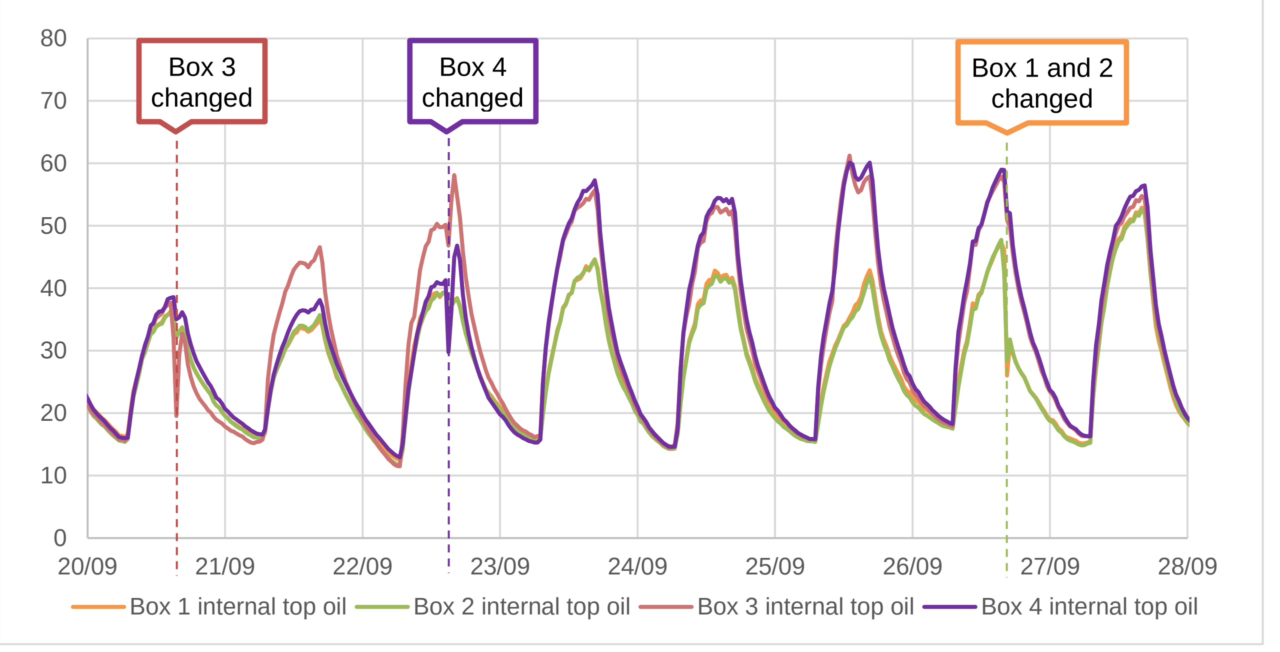

Figure 4: Top oil temperatures as each box is changed from water filled to oil filled. All graphs show temperature in °C.

2.2 Paint testing on assets exposed to the sun

The three colours that were tested for outdoor use were grey, silver and white. Boxes 1, 2 and 3 were painted with an undercoat of the same type, and then the coloured paint applied on top. The image below shows the boxes with the colour applied.

Figure 5: Colour changes for outdoor paint testing; box 1 (grey), box 2 (silver), and box 3 (white).

The boxes were loaded identically, and data collected as to their internal and external temperatures. This test was carried out over 26 days, and the graph below shows the conditions over that period, including ambient temperature in the sun and in the shade, and the status of the heating element. Where the ambient temperature in the sun is significantly higher than that in the shade, this indicates that this was a sunny period where solar gain was impacting temperatures of the boxes.

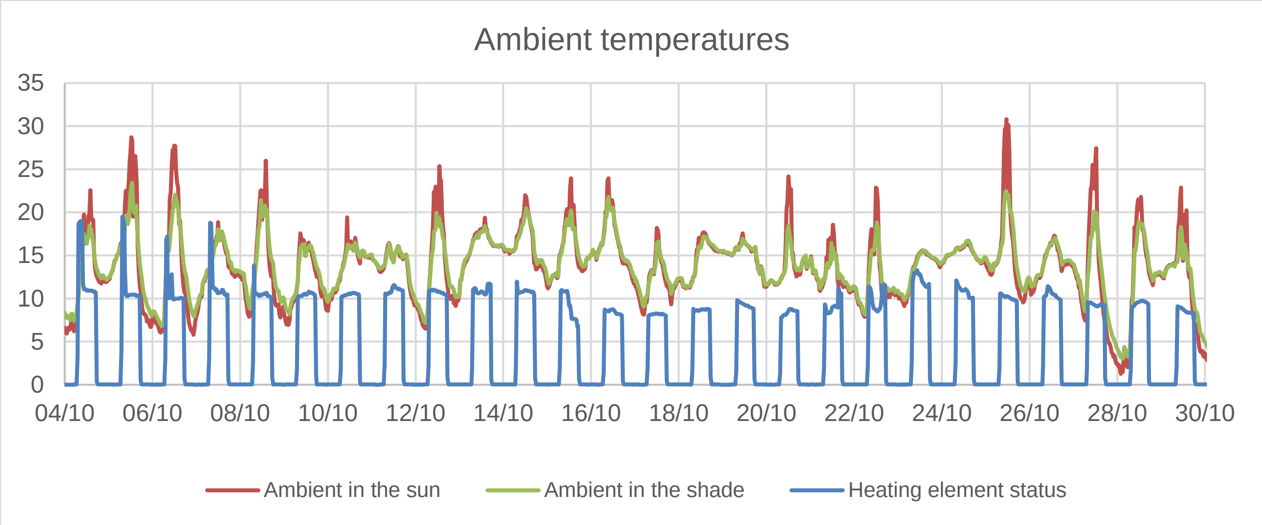

Figure 6: Conditions over the outdoor painted asset trial. Where the ambient temperature in the sun is significantly higher than that in the shade, this indicates that this was a sunny period where solar gain was impacting temperatures of the boxes. All graphs show temperature in °C.

The graphs below show this data on two days where there were significant periods of sunshine.

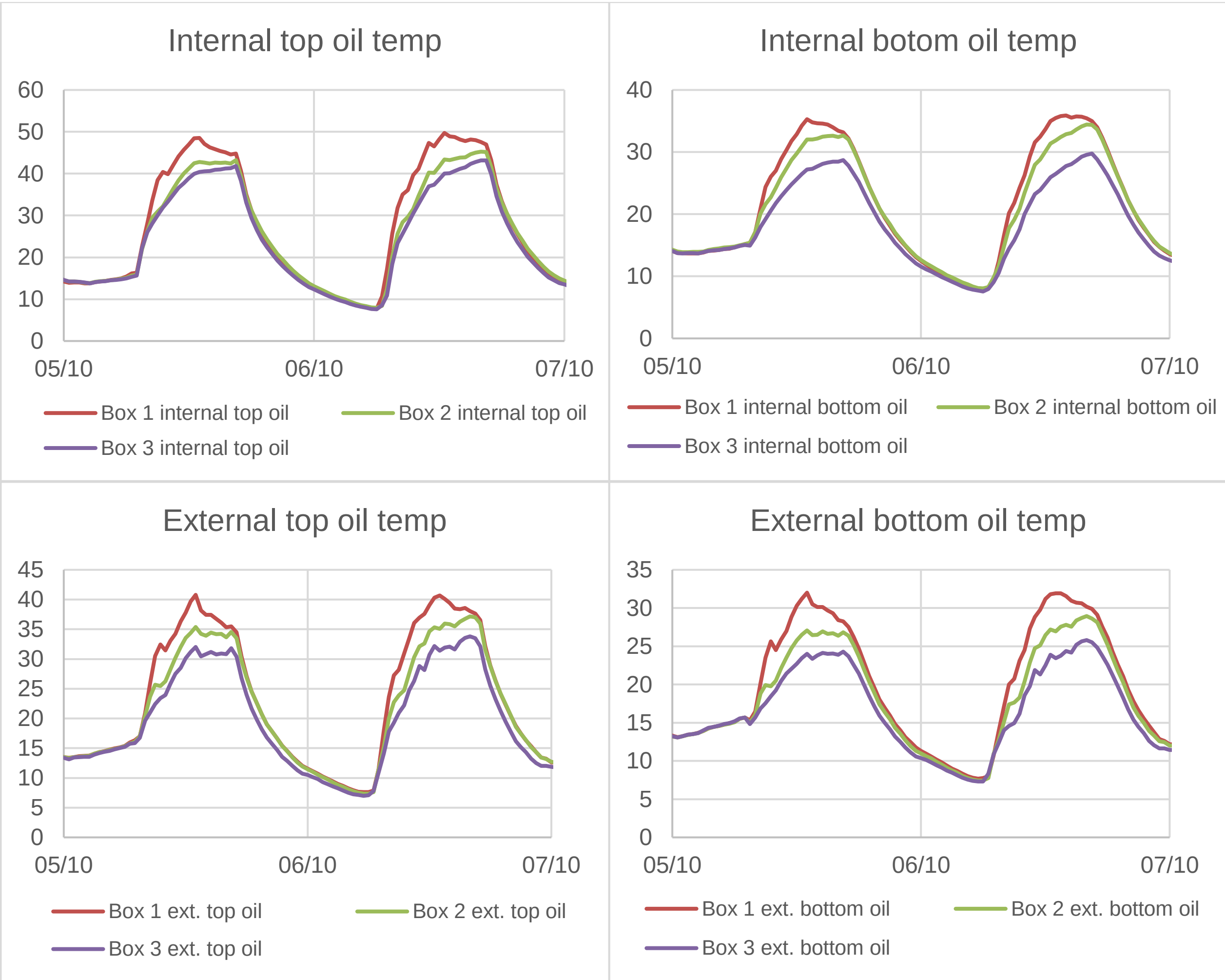

Figure 7: Comparing the internal top (top left), internal bottom (top right), external top (bottom left) and external bottom (bottom right) temperatures for box 1 (grey), box 2 (silver), and box 3 (white). All graphs show temperature in °C.

The graphs show a marked difference in the temperature of the assets during the hours of sunlight. The grey box 1 has a significantly higher temperature than the white box 3, and the silver painted box 2 has a temperature in-between. From what can be seen, there is limited impact on the temperature of the boxes when the sun is not shining.

The table below shows the average difference in temperature between box 1 (grey) and box 3 (white) for each of the positions in 'sunny' periods (where the ambient temperature measured in the sun is about 4 degrees above that in the shade), and 'not sunny' periods (where ambient temperature in the sun is less than 1 degree higher than that in the shade).

Box 1 (grey) temperature minus box 3 (white) temperature	Average difference in internal top oil temperature	Average difference in internal bottom oil temperature	Average difference in external top oil temperature	Average difference in external bottom oil temperature
'Sunny' periods	4.7	4.3	4.4	3.9
'Not sunny' periods	0.1	0.7	0.6	0.5

This analysis shows that while there is little difference between the behaviour of the boxes when not in direct sunlight, there is a difference in the impact of direct solar gain on the boxes. Box 3, painted white, is on average 4°C cooler than box 1 (painted grey).

The graph below shows the impact of box colour at times where there is significant solar radiation. It compares the difference between ambient temperatures measured in the shade and sun, and the difference in top oil temperatures between the grey box (which is at a higher temperature) and the white box (at the lower temperature). The data has been filtered for other weather effects such as high wind or rain conditions.

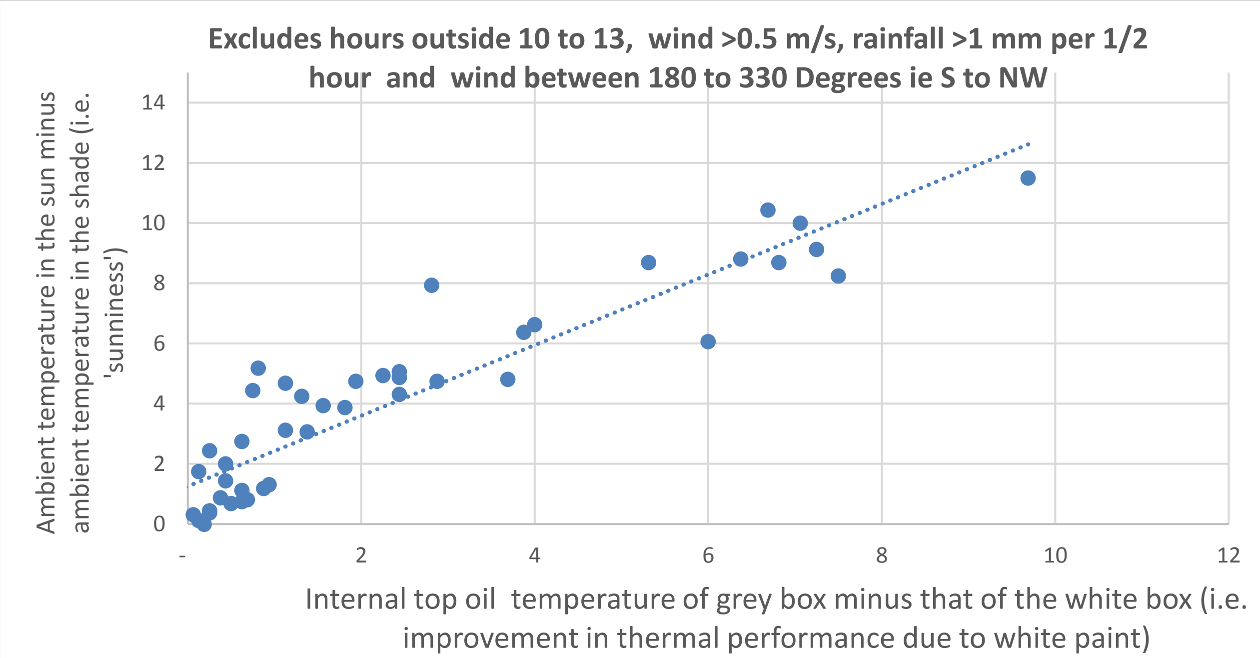

Figure 8: Illustration of the benefit of white paint over grey, showing the reduction in temperature of the box on sunny days. All graphs show temperature in °C.

This graph shows that there is a more significant temperature benefit when there is greater solar radiation. It should be noted that these tests were carried out in October. It is possible that in the summer months, further benefit may have been demonstrated.

2.3 Paint testing on heavily loaded assets

The three colours that were tested for use with heavily loaded assets to test the impact on how they give off heat. These were light grey, dark grey, and matt black. The image below shows the boxes with the colour applied.

Figure 9: Indoor colour testing; box 1 (grey, furthest), box 2 (matt black), and box 3 (light grey, closest)

The boxes were placed indoors with local ambient temperature monitoring. The heating elements were loaded identically between boxes. The graphs below compare the temperature measurements for these three boxes. Note that the heating thermostat for box 3 cut out part way through the test, indicated by a red asterisk.

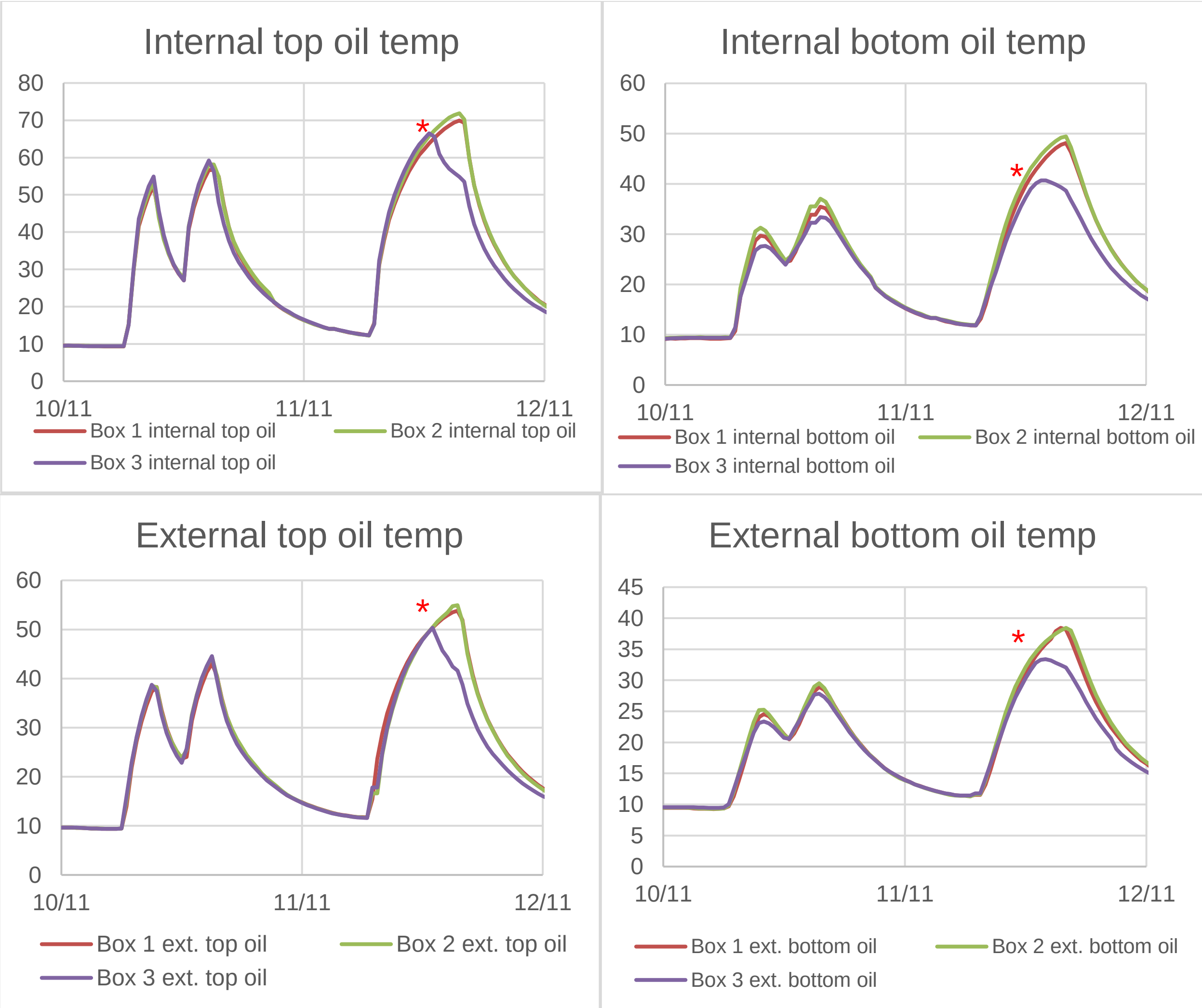

Figure 10: Comparison of the internal top oil (top left), internal bottom oil (top right), external top oil (bottom left), and external bottom oil (bottom right) temperatures for box 1 (grey), box 2 (mat black), and box 3 (light grey). * Note that the heating thermostat for box 3 cut out part way through the test. All graphs show temperature in °C.

The data shows little evidence that the black box (box 2) performs better than the other boxes, either by reaching a lower maximum temperature or by cooling more quickly. There are indications that Box 3 (light grey) performs the worst; it has the steepest temperature rise, and is slightly warmer than the other boxes at the internal top oil sensor position, which is the most critical position as it is the warmest. This has not been fully explored due to the thermostat cut-off within the box 3 heaters, however, this does seem to be a repeatable result. The performance of boxes 1 and 3 (dark grey and black) are almost identical.

The temperature of box 2 is higher than that of box 1 and 3 for bottom oil level positions. This may be due to the position of the boxes; box 2 is between boxes 1 and 3, and heat may be being transferred between boxes preventing the cooling of box 2.

The boxes were re-arranged so that they were further apart, and the experiment re-run. The graphs below compare the external temperatures of the boxes in this position.

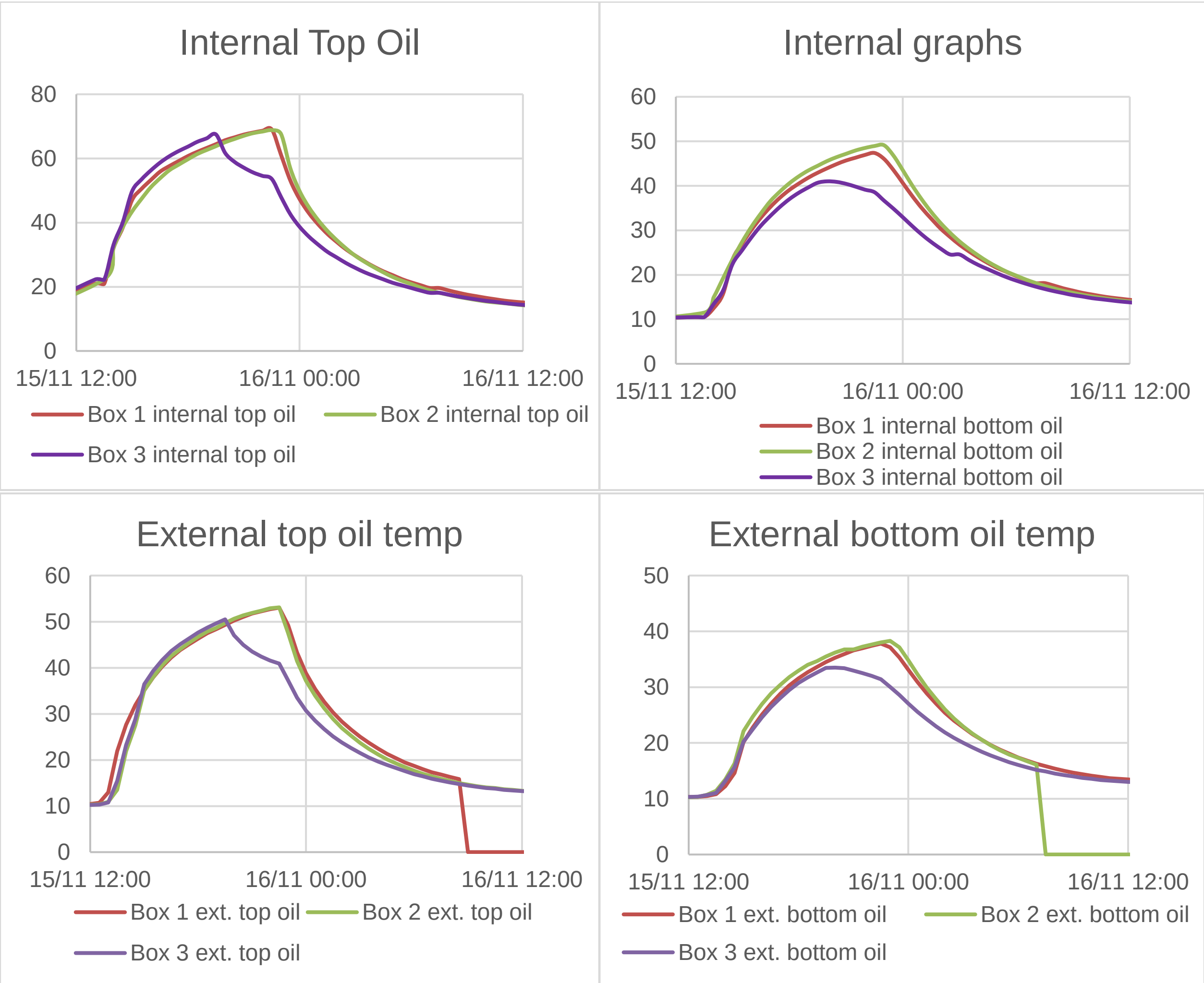

Figure 11: Showing the external top and bottom oil temperatures for box 1 (grey), box 2 (matt black), and box 3 (light grey). Note that the heating thermostat for box 3 cut out part way through the test. All graphs show temperature in °C.

The graphs show little improvement to the thermal performance of box 2.

2.4 Results and recommendations of the paint testing

Paint options are low cost, and with easy applications, and therefore could be an attractive method of cooling or improving the thermal performance of assets.

The testing suggests that using white paint to reduce solar gain in assets that are exposed to direct sunlight may be effective. Though the testing was not aiming to produce an accurate prediction of benefits, the simulated PMT painted white was more than 4°C cooler on average at the top oil level than the grey unit. While this improvement is relatively small, it is consistent.

Assets are likely to experience solar gain constraints on loading whilst they are supplying significant daytime peak load in the summer, for example, due to supplying air conditioning or EV charging loads, or connecting PV generation. With the increased take-up of low carbon technologies, these instances may increase rapidly.

As the costs of upgrading PMTs are relatively low, the cost of mitigating solar gain must also be low to ensure the business case. However, the benefits of avoiding the need to upgrade a PMT with solar gain constraints to a ground mounted transformer will be higher and might warrant mitigation works. As painting a PMT within the trial would require an outage, it is suggested that they are not included in the trial.

For outdoor ground mounted assets, the cost of upgrade is higher, and the requirements for changing the colour are simpler, not requiring an outage to paint assets. While the testing did not directly simulate these assets, it is assumed that the qualitative learning is valid across all applications where assets could benefit from protection from solar gain. Therefore, it is considered worthwhile to carry out paint trials on outdoor transformers.

Substation buildings may also benefit from solar reflective paint. It is noted that this would result in a significant aesthetic impact, particularly where buildings are being changed from a dark colour to a light one. Investigations would have to take place to understand if this change in colour would be an issue with the public. This is an integral part of the planning for the cooling deployment to be carried out separately to the work covered by this document. However, allowing for this, it is recommended that some sites are selected for trial of substation colour change.

The indoor testing of painting methods aimed to indicate if an improvement in thermal performance could be achieved by increasing the surface emissivity of an asset which was internally heated. The testing indicated that there is a marginal difference between different colours of boxes. From this, the recommendations are that indoor transformers and other heat generating assets should be a dark colour, though the improvement in performance observed is marginal and there is little difference at all between the performance with dark grey or black paint. Within the Celsius cooling technology trials, it is recommended that this technology should only be considered for assets that are of a particularly light colour, and where the ambient temperature surrounding the asset is likely to be relatively low, for example shaded outdoor assets.

The trials show some evidence that there is some small thermal interaction between transformers that are very close together, and so adequate distance between assets may be important. This aspect will be explored more thoroughly during the later stages of the Celsius project.

These tests were designed to provide an indication of potential of the technologies, not to provide an extensive or thorough test. They are based on approximations of substation equipment, and a small number of repeat tests. More complete testing, including several repeats at varied loading, may provide a more thorough picture.

3 Technology Investigation: Pole mounted transformer shade

3.1 Initial shading design

The pole mounted transformer (PMT) shading concept had previously been proposed at a high level by Ricardo. The concept is for a simple sun shade fixed to the pole that protects the transformer from radiation. Careful design considerations will have to be made depending on the configuration of the transformer and associated assets (for example, cabled PMTs verses PMT with HV lines at the top of the pole structure). Installation methodology and requirement considerations are also important.

It was proposed the shade be made of a meshed or grating material, to allow air and heat to flow through, whilst still providing significant shading. A GRP moulded grating material was selected, for the following reasons:

- **Excellent Chemical and Corrosion Resistance** – Withstands the most corrosive conditions to ensure solid structural integrity in tough environments.
- **Lightweight** – Less than 50% of the weight of steel grating.
- **Electrically and Thermally nonconductive** – Eliminates electrical / thermal hazards.
- **Long maintenance free life** – Requires no scraping, sandblasting or painting thus reducing life cycle costs.
- **Fire Retardant** – Grating has been tested to BS476: Part 7 that covers fire tests on building materials and structures, the grating met the class 1 flame spread rating.
- **Choice of colours & top surfaces** – A selection of colours are available allowing options for colour coded risers for mechanical, fire etc.

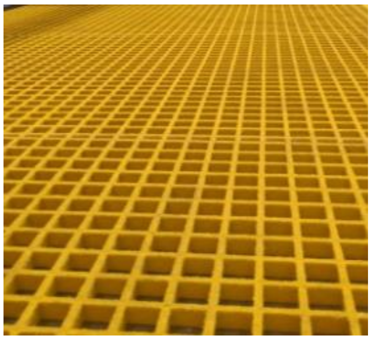

Figure 12: GRP Moulded Grating - chosen for shade material to allow air and heat to pass through, while providing significant shading.

The test apparatus described in Section 2.1 was used to investigate the effectiveness of the shade. The image below shows the testing apparatus for the initial shade design which was applied to box 4. This test rig aimed to test the principal of having a single sheet shading the top of the box. The initial position of the sheet (shown in the left-hand picture in figure 6) was assessed as being too high to effectively shade the box, and the sheet was therefore lowered. The new position provides a significant reduction in sunlight reaching the top of the box (see the right-hand picture below).

Figure 13: The PMT shade test rig for a simple top canopy, in the initial high position (left), and the later lower position (right), which shows the reduction in sunlight reaching the lid of the box.

This test rig was compared with the four other test rigs to determine the impact of the shade canopy. The graphs below show the internal and external top oil temperatures for each box over the same period.

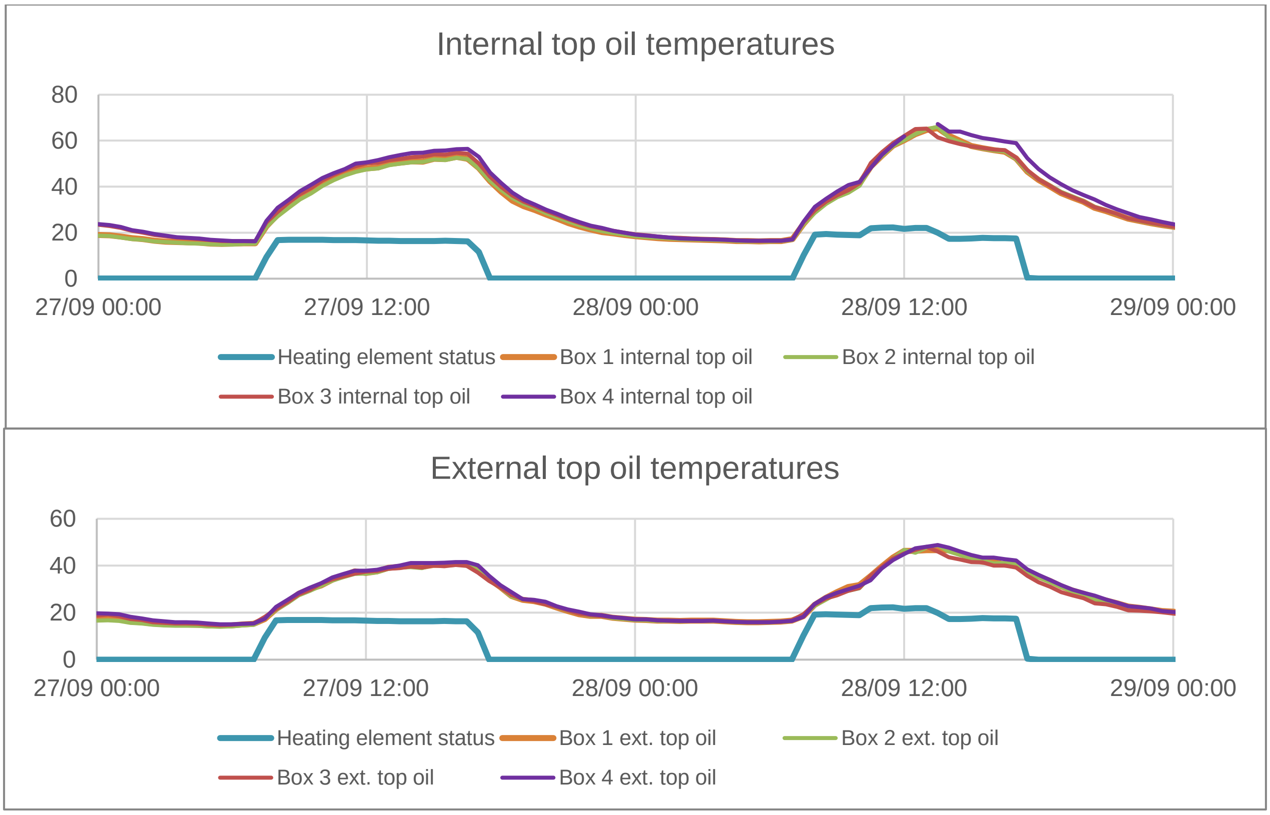

Figure 14: External top oil (top) and internal top oil (bottom) temperatures for the four boxes, where the shade has been installed onto box 4. All graphs show temperature in °C.

The graphs show the temperature impact on the surface and within the transformer oil of the shading on box 4, compared to the other boxes. There is no evidence that the overall temperature of box 4 over the two days has been reduced due to the shading. There are some indications, particularly on the internal oil temperature graph that the overall temperature has actually increased over what would be expected for an unshaded box 4.

An explanation for this could be that while the shade is preventing some solar radiation from reaching the box, it is also trapping some of the heat from the box and preventing escape. Additionally, as there is an air gap beneath the lid and above the oil, solar heating here does not have as great an impact on the operating temperature of the unit as solar heating on the side walls which are in direct contact with the oil. The design of the shade may be improved by minimising any trapping of heat, and providing shading of the side walls.

3.2 Modified shade designs

There are several more complex arrangements of shading that could bring cooling benefit without trapping the heat. Three modified shade arrangements were installed, and data collected.

As with operational transformers, the boxes are not completely filled, leaving an air gap below the lid. The temperature monitoring of the lid of the boxes is therefore less impacted by the temperature changes in the oil than those temperature sensors on the side of the boxes, and the impact of ambient conditions are more visible here.

The descriptions of each of these arrangements, along with a photograph and the associated data, is given below.

Modified shade design 1: A modified horizontal shade, with large gaps to allow heat to rise from the sides of box 4 and escape, coupled with a vertical side screen on the south side of the transformer.

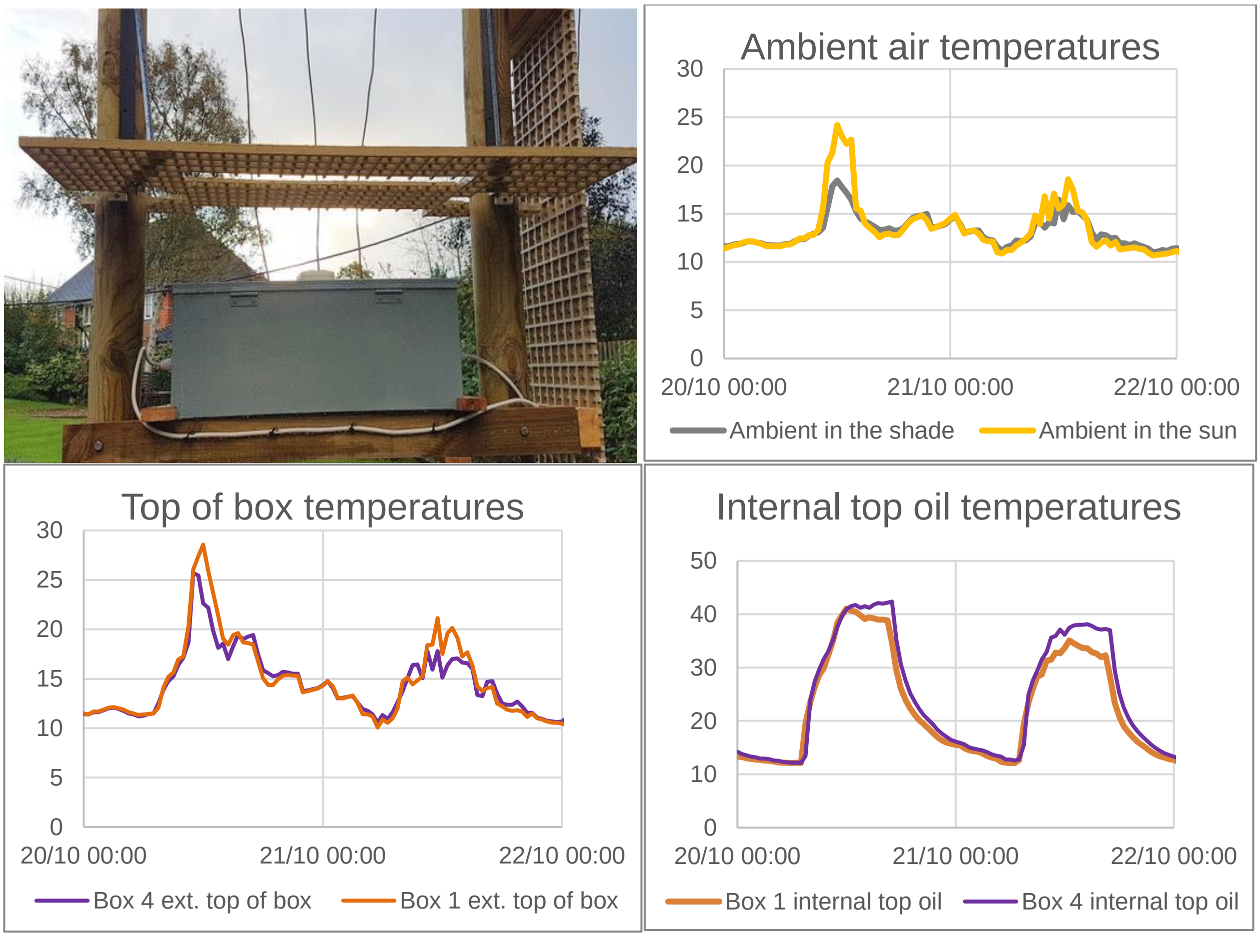

Figure 15: Modified shade 1 picture and resulting top box and internal top oil temperature. All graphs show temperature in °C.

The graph shows that there was significant solar radiation on these days, demonstrated by the fact that the ambient temperature in the sun is much greater than that in the shade at some points.

The graphs indicate that the shade is successfully protecting box 4 from a certain amount of solar radiation, as the lid temperature does not follow the pattern of the ambient temperature in the sun, and the temperature on the top of box 4 is less than that on the top of box 1 (the closest un-shaded comparison). However, again, there is little evidence that the temperature of the box is reduced as a result of the shade and the internal top oil temperature of box 4 is higher than that of box 1.

Modified shade design 2: An angled horizontal shade, designed to enable heat to be channelled out from under the shade, coupled with a vertical side screen on the south side of the transformer

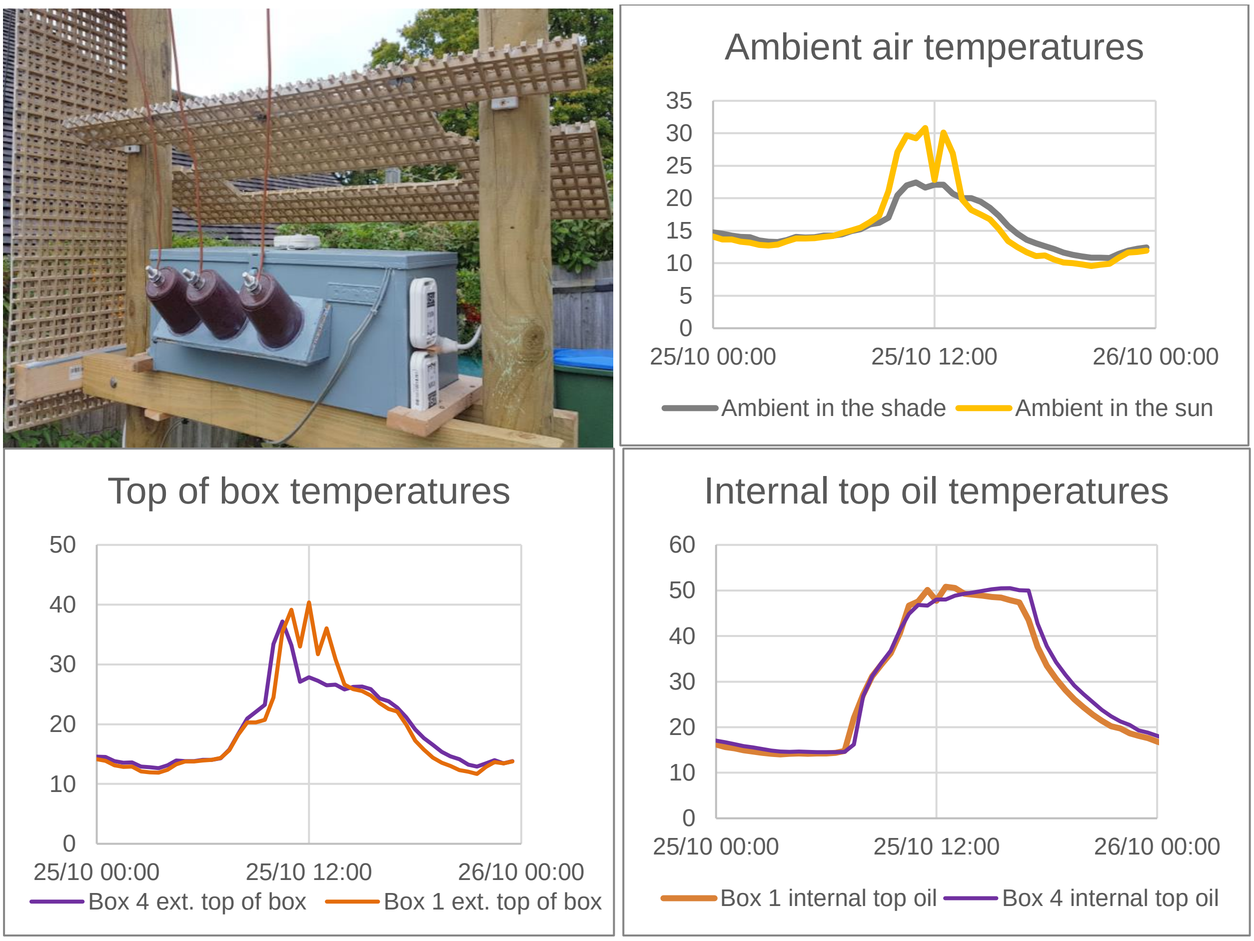

Figure 16: Modified shade 2 picture and resulting top box and internal top oil temperature. All graphs show temperature in °C.

The results of this modification are very similar to Modification 1; the graph shows that there was significant solar radiation on these days, and that the shade is successfully protecting box 4 from a certain amount of solar radiation, as the top of the box temperature is lower than that of box 1. There is an early rise in temperature potentially due to solar gain, and this is likely to be because the angle of the sun in the early part of the day is such that the sun hits the box from the east, where there is no shade.

There is some indication that there is a small shading benefit as the internal top oil temperature of box 4 is slightly lower than that of box 1 in the first half of the day. However, the benefit is marginal, and the situation is reversed in the afternoon.

Modified shade design 3: The same angled horizontal shade and vertical side screen, with additional angles shade on the east side of the transformer.

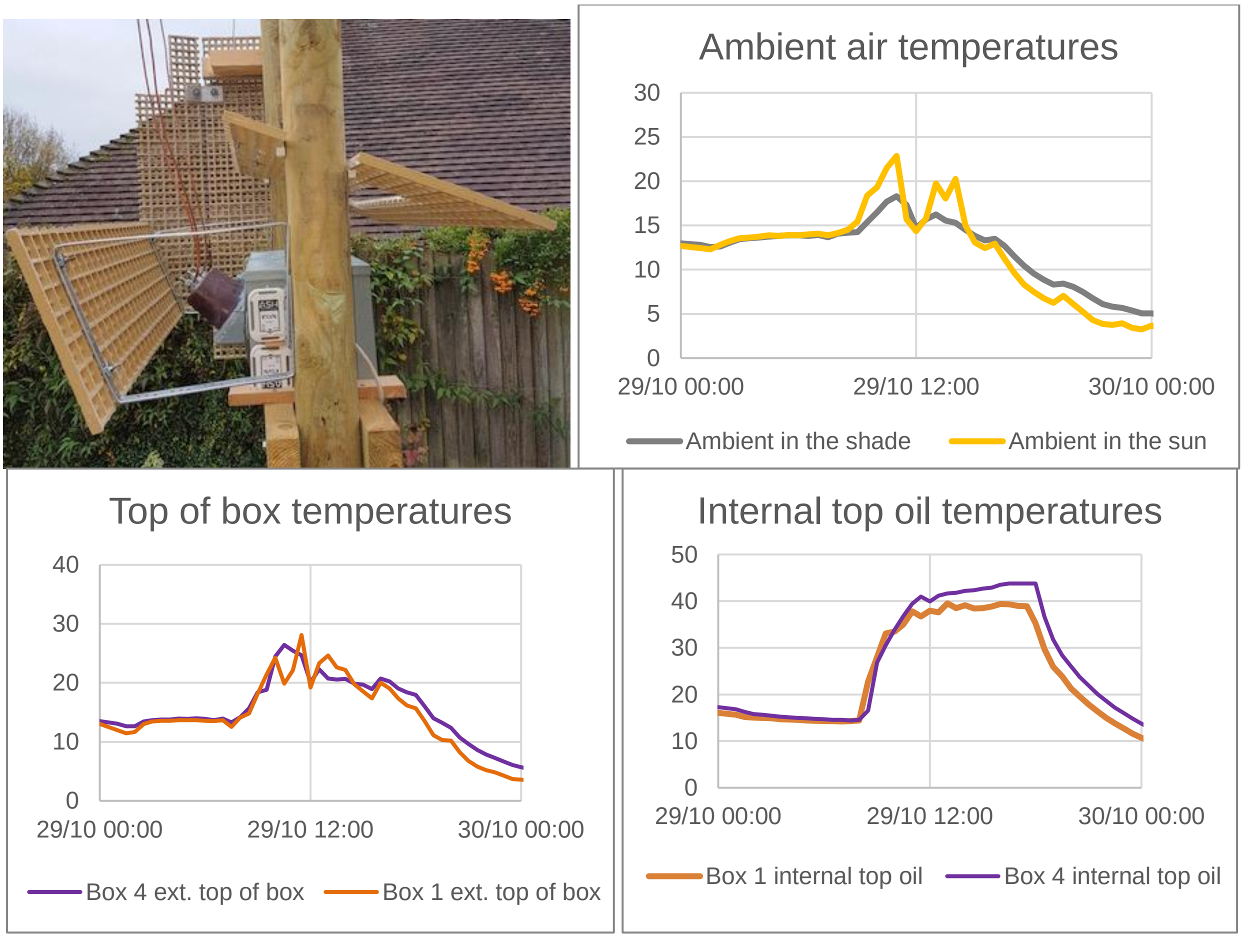

Figure 17: Modified shade 3 picture and resulting top box temperature. All graphs show temperature in °C.

There is only limited solar radiation on this day, but the graph shows that the temperature on the top of box 4 responds to temperature early in the day, and then is shaded. Again, there is limited evidence of a marked improvement in temperature of box 4, as the internal top oil temperature of box 4 is greater than that of box 1. This is likely to be because the benefits of the shade, in the avoided solar radiation are not being felt, and the heat trapping effect is still a significant factor with this shade design.

3.3 Results and recommendations of the shade testing

There are a number of considerations around the implementation of PMT shades within the Celsius Retrofit Cooling Trials.

Though a shade may prevent solar gain to a transformer, the testing that was carried out showed that shading the top of the transformer does not result in a significant temperature benefit. This is likely to be because any benefits gained from shading are counteracted by the shade structure itself trapping heat and preventing it from escaping the transformer. Additionally, as there is an air gap beneath the lid and above the oil, solar heating here does not have as great an impact on the operating temperature of the unit as solar heating on the side walls which are in direct contact with the oil. The design of the shade may be improved by minimising any trapping of heat, and providing shading of the side. If this solution was selected for trial, the design of the shade must be carefully considered to provide maximum useful shade, and minimum heat trapping. Therefore, it is probable that a vertical shade protecting the sides of the transformer would be most effective, as it would bring the benefit of protection from solar gain, while allowing heat to escape upwards.

Other important design considerations add to the complexity of this solution, including the need to consider the installation methodology, the need for resilience in all weather conditions, and concerns about wildlife sitting and nesting on the structures (this is mostly a consideration for horizontal shades, though other shade designs should also consider it). Another consideration is the visual impact of the solution which would be in sight of the public.

A complex shade design, such as one shading the side of the transformer would be complex to design and install, potentially needing to be bespoke per installation.

For these reasons, it is unlikely that PMT shades are a suitable solution for implementation during the Celsius trials. Further to this, the ground mounted transformer and substation building shade concepts, which are both potential trial technologies, should be carefully considered based on the learning from this testing.

4 Technology Investigation: Ground mounted shade

4.1 Requirement for protection of equipment from solar gain

Solar heating of substations and their assets is observed particularly in Glass-fibre Reinforced Plastic (GRP) enclosure substations in direct sunlight, which then heats the air in the substation heating the assets and limiting their ability to expel heat, and for outdoor substations where the assets themselves can be directly exposed to solar gain.

The retrofit monitoring trial of Celsius has provided some evidence of solar heating in substations. The graph below shows the top oil and ambient temperatures, and the utilisation of an outdoor, exposed substation. It can be seen that the shape of the asset temperature data is not solely linked to the asset utilisation, and that the environment is also having an impact. For example, on 28/09/17, the top oil temperature rises about 4.5°C higher than the other two days which have comparable utilisation. Note that the ambient temperature is higher on this day, which is to be accepted on a sunny day, but the rise in asset temperature leads the rise in ambient temperature, which suggests that there is another cause for the higher temperature. This could be the impact of solar radiation. Another point to note on this graph is a dip in load in the middle of the day on the 28/09/2017 (as indicated by the black dashed box), which may be due to solar panel arrays connected to the circuits. If this is the case, then it should be noted that the heating impact of the solar radiation may be counteracted by the decrease in load at this time, and that for sites where solar generation is not installed, the impact may be much greater.

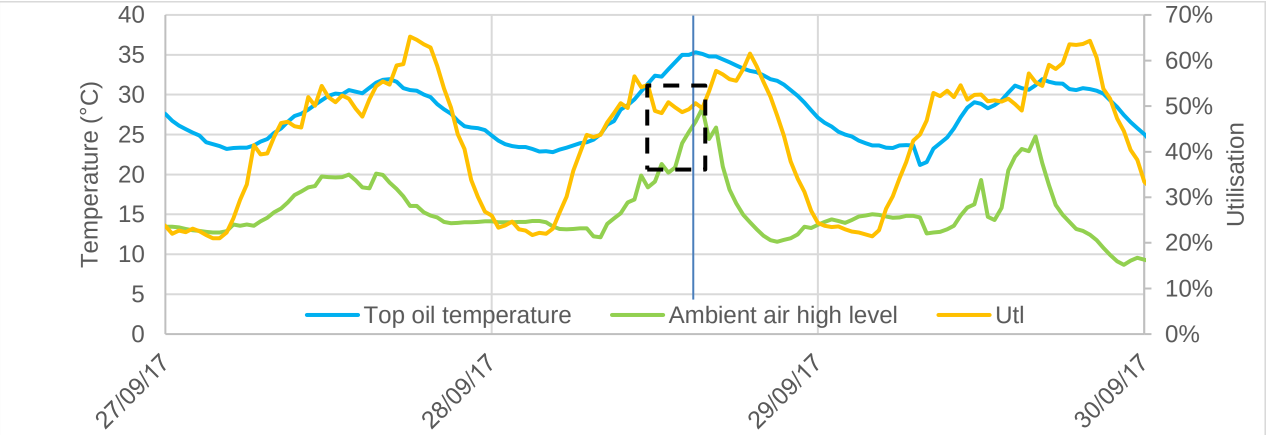

Figure 18: Top oil and ambient temperatures, and the utilisation of an outdoor substation exposed to solar radiation.

It is suggested that in the case where the peak load coincides with times of solar gain, preventing solar heating of substation assets may enable the release of additional capacity by preventing the operating temperature rising above rated operating temperature at these times.

There are several important considerations to the design of a shade for an outdoor transformer or substation enclosure:

- **Physical space** – there is often only limited space available surrounding assets to be shaded, and therefore any shade solution should be compact with limited footprint area. Where footings or foundations are required, then the presence of underground cables or other obstructions needs to be considered.
- **Maintenance requirement** – network equipment at low voltage is not visited regularly for maintenance requirements, and therefore any solution should have minimal maintenance requirements, with a target of 10 years between maintenance activities.

- **Resilience** – the shade will need to be resilient to weather conditions including storms and flood. There are also potential issues with vandalism, and therefore the shade should be able to withstand reasonable levels of force and interference, and should not pose a safety risk.
- **Visual impact** – these shades will be visible to the public, and therefore should not cause a negative visual impact. This is subjective, but a good guideline is to reduce visual impact of any kind.

4.2 Possible shade solution characteristics

Ricardo has performed testing of shade solutions for pole mounted assets, with limited success. It was concluded that this was because the shade acted as a barrier preventing heat escape. There is a greater degree of flexibility with the design of a ground mounted shade, and so a wider range of material and design options can be considered.

Shades can be carefully designed to provide maximum protection from the sun, while trapping minimal heat. Maintenance requirements can also be minimised through prevention of water pooling, and robustness of design. Design will need to be developed to take into account site configuration and available space, including taking into account the presence of cables or other obstructions when considering the need for foundations and footings. .

The diagrams below show two potential shade approaches; a sale-type shade, and a chimney-type shade.

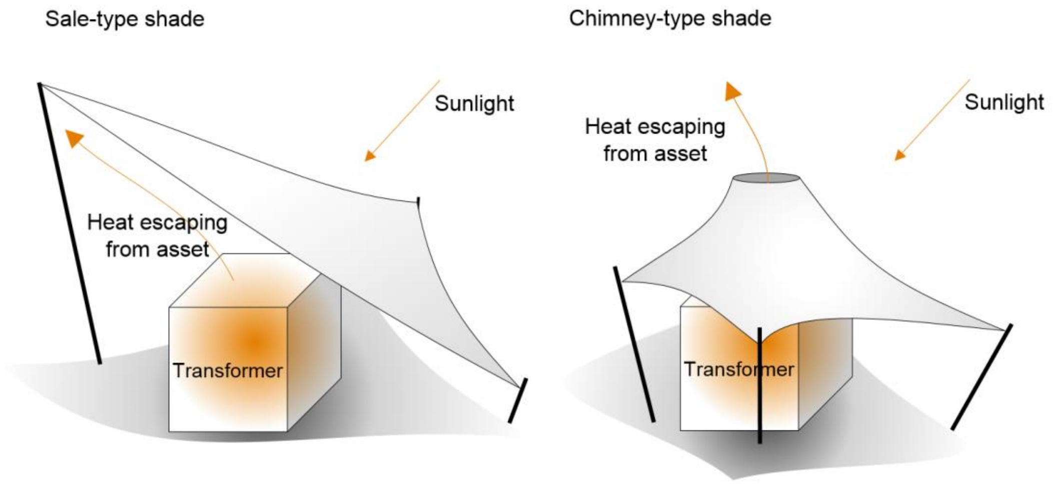

Figure 19: Two potential shade approaches, which protect against solar radiation while allowing heat to escape.

It should be noted that there will be a significant visual impact of these shade solutions, and as mentioned above, this is an important consideration. Careful thought will need to be applied to resilience to weather conditions, vandalism, and other potential causes of wear.

The shades can be deployed on transformers themselves, or substation enclosures. However, the size requirements of the shade for a substation enclosure is substantial, making design more difficult, and increasing the visual impact.

4.3 Potential Suppliers

There are a large number of potential suppliers of simple, ground mounted shades that would serve this purpose. For example:

- **Inside 2 Outside** – offers a wide range of canopies and shades, which can be tailored to needs. Initial contact has been made. Link: http://www.inside2outside.co.uk/sailshade-canopies
- **Tensile Solutions** – also offers a range of solutions, including the 'Ripple' which has wooden legs. Link: http://www.tensilesolutions.co.uk/shadesail/ripple4m/
- **Shade Solutions** – Has a range of products and a list of standard designs on the website, with prices. Link: http://www.shade-solutions.com/shop-online/shop/hyperbolic-shade-sails

Ricardo has had informal discussions with 'Inside 2 Outside' who supply permanent outdoor structures with tensile membrane covers. These discussions have informed the material in the sections above.

No formal quote has been gained for the provision of transformer shading. It is assumed that in business as usual, where design options can be standardised, the cost per shade is in the region of £400 (based on high level conversations with Inside 2 Outside Ltd., and also an internet quote from 'Shade Solutions'.

4.4 Recommendations for ground mounted shades

The potential benefits of shades for ground mounted network assets and substations are uncertain, and are likely to be modest. However, if designed carefully, this could be a low cost and low maintenance technique that can be deployed for equipment that is heavily loaded in Summer and exposed to solar radiation.

It is noted that the visual impact of this solution will be significant, particularly for the larger, substation shades, and therefore the public acceptance of this will need to be tested. This is an integral part of the planning for the cooling deployment to be carried out separately to the work covered by this document.

Another consideration may be the need for Local Authority planning consent, which is likely to be of particular concern for larger, substation shades.

It is concluded that ground mounted shades could be trialled within Celsius, with a recommendation of a relatively low number of sites to be tested. This could include one example of a substation enclosure if the design and public acceptance requirements are can be met.

5 Improved substation ventilation

5.1 Requirement for improved substation ventilation

As standard, the vast majority of substations have some ventilation provision to support rejection of heat from the substation assets. However, there is a potential benefit in optimising this ventilation, allowing the substation assets to operate at a lower temperature for any given load. Simple analysis of the data gained through the Celsius retrofit monitoring trial identified 28 substations where the ambient temperature was above 30°C during September and October 2017. An example of this is shown in the graph below; the ambient temperature of Rice Street substation was up to 37°C. This site is a double transformer site, and is not heavily utilised, at only approximately 20% average utilisation over this period.

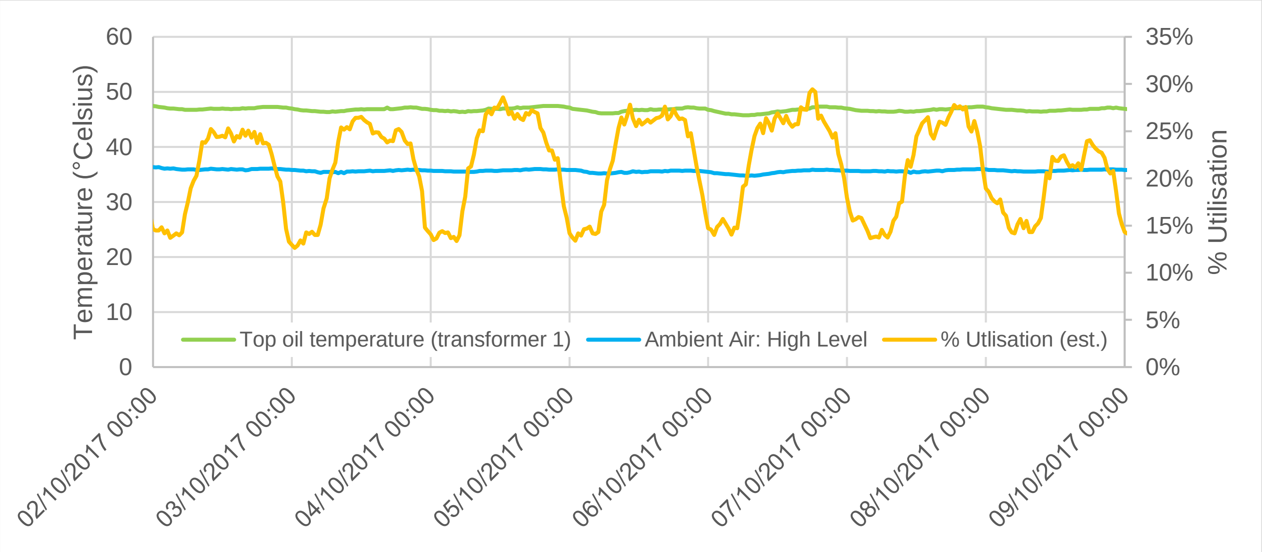

Figure 20: Graph of top oil and ambient temperatures for Rice Street - a double transformer site with ventilation problems. The ambient temperature is high, despite the utilisation being relatively low.

The configuration of LV substations varies widely – they can be a range of shapes, materials, layouts, and surroundings. Within this mix, there are some 'standard' building designs that have been used, including stand-alone brick substations, and a Glass Reinforced Plastic (GRP) substations. However, there is a significant proportion that do not conform to these standards. Often, these substations are part of a larger building, for example in basements or via back entrances. The ventilation optimisation solution will vary depending on these factors.

There are several important considerations to the design of ventilation improvements for substations:

- **Maintenance requirement** – network equipment at low voltage is not visited regularly for maintenance requirements, and therefore any solution should have minimal maintenance requirements, with a target of 10 years between maintenance activities.
- **Resilience** – any alterations to the building structure will need to be resilient to weather conditions including storms and flood. There are also potential issues with vandalism, and therefore the solution should be able to withstand reasonable levels of force and interference, and should not pose a safety risk, including external changes, which may need anti climbing measures.
- **Visual impact** – these substations are often located in positions visible to the public, and therefore any building alteration should not cause a negative visual impact. This is subjective, but a good guideline is to reduce visual impact of any kind.

5.2 Approach to improved ventilation solutions

Ricardo and ENW have had initial discussions with the National Physical Laboratory (NPL) about carrying out analysis and providing the recommendations about optimised ventilation methods. The work that they have carried out as part of the Celsius project to date has included the development of a set of models that represent a range of distribution substation topologies, and have run and validated thermal flow simulations that represent the heat distribution and flow of air in the room.

These models can now be further used to develop recommendations for changes to substation ventilation arrangements. Initial indications from these studies is that the ventilation arrangement are not currently optimised, and that there are various measures that can be taken to improve the flow of heat from the assets.

For example, alterations to sites might include:

- Changing the size and design of vents
- Changing the position of vents
- Addition of a chimney vent in the ceiling or walls

As mentioned, 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. In order to bring benefit to as wider range of sites, the approach to improving the ventilation of substations will be to consider three categories of sites:

- ‘Standard’ stand-alone brick built sites
- ‘Standard’ stand-alone GRP sites
- Unusual sites

The two standard site types can be investigated in turn, and suitable optimisation options developed. These solutions can be deployed for testing over a number of Celsius substations to investigate and prove the benefits. This could be an efficient way of testing the benefits on comparable sites. More than one option could be developed for each standard type, each being tested on multiple sites.

For unusual sites, the solutions will need to be developed on a case-by-case basis. This is a more labour-intensive process. However, it is often the more unusual sites which show the most significant temperature issues, and could provide the most significant benefit. The work could be reduced by providing a check-list and standard guidelines that could be applied at all sites.

It is likely that once designed, the alterations themselves could be undertaken by an established ENW civils contractor. Simple changes, such as changing the size of vents or adding new vents in walls, are likely to be low cost. More significant changes such as the addition of a chimney may be more expensive. However, an indication of benefit will be gathered during the NPL design and development process and decisions can be made at that time to understand the balance of cost and value.

5.3 Recommendations for improved substation ventilation

From the Thermal Flow Study work undertaken to date by NPL, there are initial indications that significant improvements may be possible to existing ventilation arrangements. The expected benefits can be understood further during the design process, which will be carried out by NPL. It is therefore recommended that improved ventilation is included in the Celsius trial.

As detailed above, there are three categories of sites, including two distinct ‘standard’ site types, for which multiple options could be developed. It is recommended that two options are trialled, potentially one simplified, low cost option, and one fully optimised option. These can be trialled separately.

The third site type is described as ‘unusual sites’, for example, unusual room shapes and dimensions. Examples of these can be identified separately, and solutions developed. Support from NPL can be provided to establish a set of guidelines to use to improve ventilation.

6 Passive cooling site selection

6.1 Site selection requirements

The Celsius cooling trial will include 100 sites, selected from the pool of 520 substations included in the retrofit monitoring trial. Separately to the work reported here, four active solutions have been identified. These active solutions will be trialled at 40 sites, leaving 60 sites to trial passive solutions.

The table below details the categories of cooling technology to be trialled, following the testing and research detailed in the sections above. Also listed is the number of technologies recommended to be included, based on considerations of suitability for trials and expected benefits. Note that there will be an additional list of ‘back-up’ sites to be used if selected sites are found not to be suitable. There is also a summary of the site selection requirements.

Technology	Number	Site Selection Criteriaow with solar gain
Colour change for ground mounted assets	10	Outdoor assets impacted by solar gain should be painted with a light colour. Assets with high load and temperature, shaded from the sun should be painted a dark colour. Note this is only suitable if the ambient temperature is kept low, so is relevant for shaded outdoor assets. A mixture of sites with and without PV connected is preferable. Note: Implementation on substations will have a particularly significant visual impact and the public acceptance will need to be tested. For this reason, selection has focused on outdoor transformers.
Sun shade for ground mounted asset	5	Outdoor assets or substations impacted by solar gain. A mixture of sites with and without PV connected is preferable. Note: Implementation on substations will have a particularly significant visual impact and the public acceptance will need to be tested. For this reason, selection has focused on outdoor transformers.
Improved substation ventilation for ‘standard’ GRP substations	20	GRP unit substations with high asset and ambient temperatures. Two options could be tested, for example with ten examples of one and five of the other.
Improved substation ventilation for ‘standard’ brick substations	20	Stand-alone brick substations with high asset and ambient temperatures. Two options could be tested, for example with ten examples of one and five of the other.
Improved substation ventilation for ‘unusual’ substations	5	Substations that do not fit into the ‘standards’ listed above, but are experiencing high asset and ambient temperatures. The number tested will depend on the ability to identify site examples, and options for improvement.

6.2 Site Selection Methodology

The sites to be selected fall into two categories:

- **Outdoor substations** – This is for implementation of the colour change and sun shade methods. Target number: 15 substations with 10 back-ups.
- **Indoor substations** – This is for implementation of the improved ventilation types, colour change to dark colours, and also for the three active cooling solutions selected separately to the work described by this document. Target number: 45, with 13 back-ups for the passive solutions.

Each of these site types were analysed in turn to identify candidate sites for selection. This selection was based on the building type, the asset and ambient temperature profiles, and the utilisation of the assets.

6.3 Site Selection – Outdoor Substations

Outdoor substations for inclusion on the cooling trials were selected based on the following criteria:

- **Substation type** – Outdoor substations
- **High top oil temperature** – taken from the 28 days following 19th September 2017. The sites with the highest temperatures were prioritised.
- **High utilisation** – taken from the 28 days following 19th September 2017. The sites with the highest utilisation were prioritised.

The selection list was then prioritised by the maximum top oil temperature reading. The selection is shown below:

		Ave. top oil temp	Max top oil temp	Average Utilisation
Headlands	620620	24.60	43.00	32%
St Wilfrids Church	417006	32.09	42.81	52%
Moss Ln	216962	31.15	42.38	53%
Broad Lane	216144	26.76	42.06	47%
Halecroft Hale Rd	410261	34.10	41.94	52%
Greenways	410248	32.00	41.31	45%
Chisacre Dr	211425	29.16	40.31	30%
St Leonards	415341	29.57	39.50	20%
Crosthwaite CT	621856	25.92	38.06	43%
Tesco Sale	171784	27.75	37.88	43%
Disley Main	331559	30.62	37.88	37%
CWS Broughton	165680	25.98	36.81	42%
Schola Green Lane	641928	23.93	36.63	32%
Mount St	232186	32.92	36.06	21%
Whitelands Rd Ind Est	325847	22.96	35.69	36%

In order to ascertain if the sites are suitable for the selection, it is recommended that additional information is needed, including:

- **If the assets are exposed to sunlight** – the shade and light-coloured paint are only suitable for assets exposed to sunlight. Shaded assets may be considered for dark paint increasing emissivity, but only if they are currently a light colour.
- **If the assets have solar generation connected** – it is desirable to have a mixture of sites with and without solar connected if possible. This information is also important in the analysis of the benefits during and following the trial.
- **If the site is suitable for shade installation** – this includes if there is physical space for the shades, including any need for foundations or footings.
- **If the site is suitable for painting** – can the asset be safely re-painted to change the colour

- **If there are any issues with public acceptance with any cooling technology at the site** – this is part of a separate piece of work within the Celsius project.

This information will allow us to determine which technology should be used, or if sites are unsuitable.

Where sites are considered unsuitable, then they can be discounted from the selection and replaced with another site. The following list is a set of back-up sites, in priority order, with which to replace unsuitable sites. If more site options are required, they can be provided.

		Ave. top oil temp	Max top oil temp	Average Utilisation
Silverwood Avenue	171904	28.17	35.69	32%
Manor Road	455561	26.68	35.63	43%
Thurstonfield	650168	25.35	35.00	63%
Maple Ave	216923	25.50	34.81	40%
Brookfield Industrial Est	325835	24.92	34.75	27%
ATE Grimsaragh	177479	23.83	34.69	19%
Tame St	327078	26.22	34.50	24%
Beaufort Rd	452011	26.40	34.19	43%
Dialstone	171538	24.44	33.94	22%
Coke Street	165129	27.23	33.88	40%

6.4 Site Selection – Indoor Substations

Indoor substations for inclusion on the cooling trials were selected based on the following criteria:

- **Substation type** – Building fabric, including brick built substations, glass-reinforced plastic (GRP) substations, and substations that are part of a larger building.
- **High top oil temperature** – taken from the 28 days following 19th September 2017. Where possible, the sites with maximum top oil temperatures of 40°C and above were prioritised.
- **High ambient temperature** – taken from the 28 days following 19th September 2017. Where possible, the sites with maximum ambient temperatures of 30°C and above were prioritised.
- **Monitoring Type** – Monitoring types 1 and 1a were prioritised where possible, as this type has the most detailed monitoring of the substation and assets. Note that the type 1a sites are being investigated to increase their loading, which will make them more suitable for cooling methods. When more information is known about this
- **Inclusion in the Thermal Flow Study** – All sites included in the Thermal Flow Study (a modelling study being undertaken by the National Physical Laboratory as part of Celsius) were considered for inclusion in the trials, as there are existing detailed models for these sites.

Below is the selection for the three categories of improved ventilation: GRP, brick built, and unusual building type. Where assets within these substations have light coloured assets, then colour change to a dark colour may also be considered, particularly if they are heavily loaded.

Site selection for the trial of ventilation techniques for standard standalone brick built substations (20 sites):

Site	Code
Acorn st	216005
Alder ave	212304
Angle st	231178
Brompton rd	171262
Devonshire st n	171538
Dudley st	165136
Duke st	332644

Green ln	231207
Heaton cl	414869
Helmside drive	641915
Hough ln	415142
Lancaster ave	216809
Leicester ave	212726
Offerton dr	331286
Punch bowl	217132
Spendmore ln w	414690
St georges st	217277
Victoria rd eccles	165500
Wentworth rd	211952
Whitefriars	165671

Site selection for the trial of ventilation techniques for standard standalone GRP substations (20 sites):

Site	Code
Albrighton est	415402
Ashley walk	178381
Ashmount road b	616197
Ashton 6th form college	328629
Audley ave	166531
Avondale rd stretford	165935
Cawdor st	166924
Chelsea rd	165304
Coppice ave	171222
Direct line	166915
Eustace st	231757
Manor pk	167259
Palace rd	338363
Prismo products	419894
Rusholme pl	172004
Saddleworth school	327652
Saunders wood	417305
Shap rd laundry	659436
Town bridge	218333
Whinnie hs rd	636386

Site selection for the trial of ventilation techniques for non-standard substations (5 sites):

Site	Code
Dene rd	171526
Emmanuel st, preston	410017

Mount st rmu	165455
Portland gr	332812
West end road	641975

In order to ascertain if the sites are suitable for the selection, it is recommended that additional information is needed, including:

- **If the site is suitable for ventilation changes** – this includes if there is the necessary access and the building is suitable for making changes.
- **If the site is suitable for painting** – is the asset a light colour, and heavily loaded, and can the asset be safely re-painted to change the colour
- **If there are any issues with public acceptance with any cooling technology at the site** – this is part of a separate piece of work within the Celsius project.

This information will allow us to determine which technology should be used, or if sites are unsuitable.

Where sites are considered unsuitable, then they can be discounted from the selection and replaced with another site. The following list is a set of back-up sites, with which to replace unsuitable sites. If more site options are required, they can be provided.

Some sites listed above are on the 'back-up' lists for the selection of active solution deployment. If these sites are required for trial of the active cooling technologies, because a site in their site selection is unsuitable, then the active cooling technology trial takes priority and the site is removed from the lists above. That site can be replaced in one of two ways; the site deemed unsuitable for active cooling methods should be considered for suitability for passive cooling trial, or a site can be taken from the passive cooling backup lists below.

Back-up sites for the trial of ventilation techniques for standard standalone brick built substations:

Site	Code
Aked cl longsight	171082
Helsby way	332455
Jessel cl	171039
Windsor rd prestwich	165122
Woodend ln	320618

Back-up sites for the trial of ventilation techniques for standard standalone GRP substations:

Site	Code
Buckshaw vill commercial	419910
Carnation rd	231735
Chantry walk	211945
South row	629174
Withington rd i/d	178114

Back-up sites for the trial of ventilation techniques for non-standard substations:

Site	Code
LANGPORT AVE	172047
ROMNEY RD	612788
SHACKLETON CT	165303