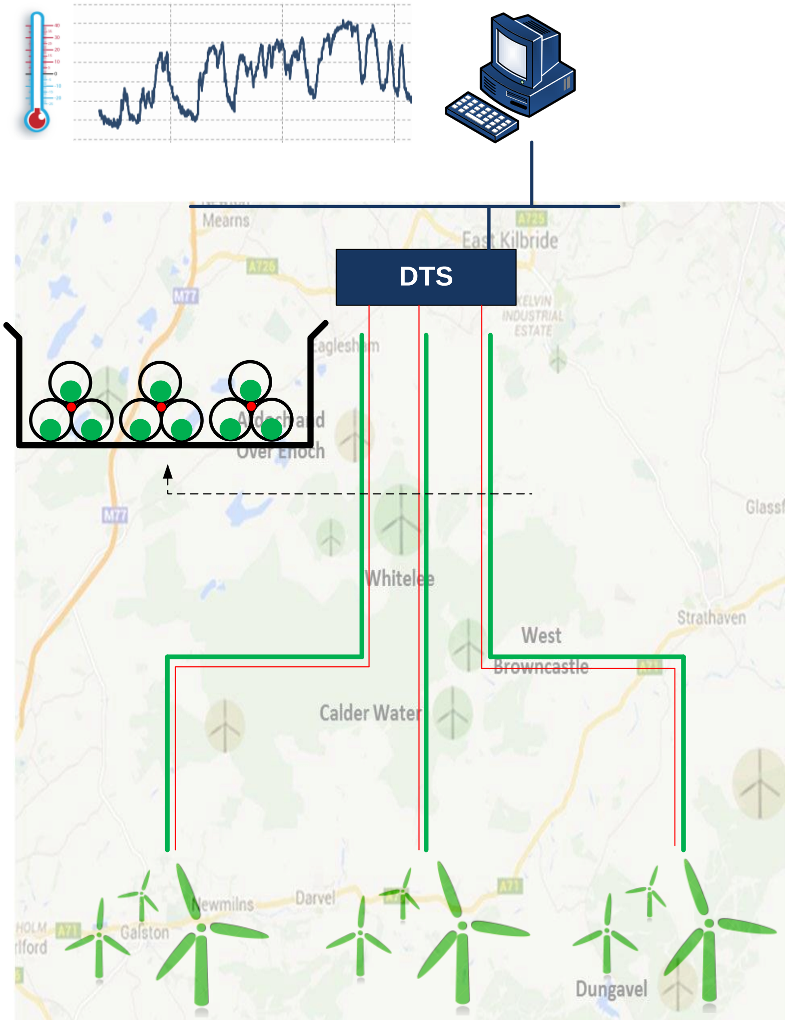
SP ENERGY NETWORKS

Temperature Monitoring Windfarm Cable Circuits



Close Down Report

Tier 1 LCNF
SPT1005
Temperature Monitoring Windfarm Cable Circuits

July 2015

LCN Fund
Low Carbon Networks

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Executive Summary

Scottish Power Energy Networks (SPEN) has trialled a Distributed Temperature Sensing (DTS) technology to monitor the real-time temperatures and calculate the dynamic thermal ratings of three 33kV cable windfarm circuits in Lanarkshire, Scotland. This project, which was funded through Tier 1 Low Carbon Networks (LCN) funding mechanism, has largely delivered its aims and objectives within the time and budget set in the project registration. A summary of the project is given in the following sections.

Project Background

Three windfarms are scheduled to connect at 33kV to East Kilbride South 275/33kV substation in an area where there is significant windfarm activity. In order to minimise costs the three cable connections will share a common trench for the initial 10.7km length from the substation. Given the close proximity of the three 33kV windfarm cable circuits each has been de-rated to 32.2MW, based on standard design principles.

Two of the three windfarm developers have subsequently asked about the prospect of increasing their generation capacity in the future and if any spare headroom capacity might be available.

The project funding will include for the installation of micro ducting with optical fibre for all power circuits, associated Distributed Temperature Sensing (DTS) schemes, determination of real time thermal ratings for the conductor cores, monitoring and analysis to assess spare capacity.

Scope and Objectives

The scope of the project is to determine dynamic cable ratings for three cable circuits (3 - 33kV) and assess the impact the renewable generation from the three windfarms will have on these circuits. From this analysis the prospect of further network capacity being available will be determined.

This project will help inform future cable rating calculations for other projects which could negate or postpone the requirement for upgrading/reinforcing the Distribution system.

Success Criteria

The project would be deemed successful if:

1. The temperature can be monitored across all three cables along the full cable route being monitored
2. Dynamic cable ratings are determined with associated wind generation output
3. Available headroom capacity can be determined for the three windfarm cable circuits

Details of the Work Carried Out

The project involved the installation of a DTS fibre optic system concurrently with the installation of the underground power cables of four windfarms connected at 33kV from East Kilbride South substation, namely Dungavel, Calder Water, West Brown Castle and Ardoch & Over Enoch windfarms. Three out of the four share a trench for the first 10.7km of their routes and they are also in close proximity to two existing Whitelee windfarm 275kV cables.

The following steps were considered for implementing the real-time cable monitoring system:

- Selection of the most appropriate technology for monitoring cable temperatures
- Identification of trial sites for the DTS technology and equipment specification
- Carrying out of procurement and tender evaluation
- Design of the system architecture, the communication system and the thermal models
- Installation of the DTS equipment and optical fibres
- Factory acceptance tests, commissioning and site acceptance tests
- Data gathering and system performance analysis
- Validation of the monitored optical fibre temperatures using independent sensors

The monitoring system of the new windfarms required optical fibres to be laid along the full length of the 33kV circuits, encased in micro-ducts. The gap in the trefoil formation of the 33kV cables was chosen as the optimum position for the micro-ducts and thus the optical fibres.

Since the proposed DTS system monitors the temperature of the optical fibre and not that of the 33kV cables themselves, appropriate algorithms and thermal modelling were deployed in order to calculate the DCRs of each of the cables. The DTS system monitors the optical fibre temperatures at 30-minute intervals for every 1m of the optical fibre. The DCR algorithms are also run every 30 minutes upon receiving the updated fibre temperature data.

The DCR methodology is based on an electrical-thermal analogy model, where the thermal characteristic of each layer between the optical fibre and the power cable core is modelled. The DCR algorithms were designed according to IEC 60853 and IEC 60287 and can take into account specific environments and different cable constructions and sizes.

In order to boost the confidence in the DTS system, the optical fibre temperature measurements were validated by using independent temperature sensors, Tinytags, at different locations.

The Outcomes of the Project

The outcomes of the project are outlined as follows:

1. Implementation of the DTS system for the Calder Water, West Browncastle, Dungavel and Ardoch & Over Enoch 33kV circuits.
2. Monitoring of half-hourly temperature variations of every metre of the optical fibre cables installed along the cable circuits through a user-friendly interface, DC-View, customised specifically for this project.
3. Development of transient thermal models for each of the cable circuits, which are used for estimating the core temperature of each circuit based on the corresponding optical fibre temperature.
4. Calculations of maximum core temperatures and thermal pinch point locations along the cable circuits.
5. Validation of temperatures measured by the DTS system by deploying the independent temperature sensors (Tinytags).
6. Gathering and analysis of the DTS data in conjunction with cable circuit loading data to provide learning on cable temperature profiles and causes of the thermal pinch points.

The results of initial analysis on monitored temperature data and cable circuit loadings are as follows:

- The output power of the windfarms follows a stochastic variation that may allow cable circuits to dissipate heat during high wind periods. The daily Loss Load Factors (LLF) of the Calder Water and Whitelee cable circuits from 01/01/2014 to 12/03/2015 were calculated and the results showed that for 80% of the time the LLF of the cable circuits can be below 0.5. This suggests a dynamic rating, rather than a continuous rating, could be more suitable for windfarm cable circuits. However, a DTS system should be in place to monitor the conditions and trigger the require actions to limit the cable loading when cable temperatures go beyond the permissible limits.
- The analysis of the Dungavel fibre temperature data demonstrates the mutual heat impact from adjacent cables. The surrounding temperature of the Dungavel circuit increased by around 8°C during the period when other circuits were carrying the rated output power of the associated windfarms. It should be noted that the Dungavel windfarm circuit is not energised yet and temperature variations seen along this circuit are largely due to thermal impacts of adjacent circuits.
- The maximum recorded fibre temperature is for a day with a high LLF and reaches around 40.0°C. Although we expect that the core temperature should be higher than the fibre temperature, it seems there could be headroom before reaching the maximum permissible temperature (78°C). SPEN is planning to investigate this further by carrying out data analysis on a 12-month period of data when all the 33kV circuits have been energised under sustained maximum generation conditions
- The location of thermal bottlenecks along the cable circuits seem to remain almost unchanged. That suggests using higher rated cables or back-fills for better heat dissipations at some locations may help to increase the overall thermal rating of the cable circuits.
- The causes of thermal bottlenecks identified along the cable circuits are due to:
    - Crossing point with the Whitelee 275kV cable circuit

- Change in depth of burial, for example before and after crossing a river
- Thermal effects from adjacent cables and low heat dissipation conditions, e.g. at the locations where the cable circuits are placed in a pyramid formation

The comparison between an independent temperature sensor and the fibre temperature for a 10-day period validated the accuracy of the DTS system at two different locations.

Project Performance against Aims, Objectives and Success Criteria

The project largely delivered its intended aims and objectives. The following key outcomes of the project are in line with the aims and objectives initially described in the project registration pro-forma:

- The DCR of all the 33kV cables, except the Dungavel windfarm circuit, are determined and the DCR values of cable circuits are available through the DCR and DC-View dashboards, which have been specifically designed and customised for this project. The real-time outputs of the windfarms are also transmitted from SPEN's PowerNet network to the DCR workstation. The Dungavel circuit is scheduled to be energised in the third quarter of 2015; once this circuit has been energised, the DCR values will be also available for it.
- The comparison between the maximum recorded optical fibre temperatures, representing the temperature around the cable, and the maximum permissible operating limit for cable core temperatures (78°C for 33kV XLPE) suggests that there may be additional network capacity available, which could be utilised if the windfarm developers decided to increase their outputs. This is subject to further assessment for at least a 12-month period after the Dungavel windfarm is energised in the third quarter of 2015.

The following key points demonstrate that the project has met its success criteria:

- The real-time full length (with 1 metre granularity) temperature profiles of the 33kV Calder Water, West Browncastle circuits and 10.7km (out of 21.4km) of the 33kV Dungavel windfarm circuit are now available through a user-friendly dashboard. The temperature profile of the remaining 10.7km Dungavel circuit will be available after this windfarm circuit is energised in the third quarter of 2015. The delay in energisation of this circuit was due to the change in the ownership of the windfarm after starting this project.
- The measured temperature values are then used by DCR algorithms to determine the maximum core temperature and the location it occurs. DCR algorithms use an equivalent thermal circuit simulating the thermal conditions of the cable along with the real-time optical fibre temperatures.
- The results of the DCR calculations of the Calder Water and West Browncastle cable circuits are recorded in the SPEN's data historian for every 30 minutes. The DCR calculations will be also available for the Dungavel circuit when this circuit is commissioned in the third quarter of 2015. This data may be used to estimate the available headroom for any period required.

Required Modifications to the Planned Approach

The following modifications were made to the original planned approach:

- Installation of DTS equipment at East Kilbride South substation rather than the windfarms' substations
- Monitoring the temperature of an additional cable circuit, Ardoch & Over Enoch
- Modification of the system architecture to meet SPEN's IT security requirements and incorporation to the corporate system
- Deploying independent temperature sensors for DTS validation

Significant Variance in Costs and Benefits

The total actual expenditure was £15,304 below the initial estimated total expenditure of £710,504. There have been some variations in different expenditure elements:

- IT: £11,623 overspend due to modifications required to the workstations to meet SPEN security standards
- Labour: £40,071 overspend due to additional resources worked on modifying system architecture
- Optical fibre installation: £21,627 overspend due to including Ardoch & Over Enoch in the DTS system
- DTA and DCR Equipment: £88,624 underspend due to selecting supplier through a competitive tender

The variance in benefits of this project is due to the delay in the commissioning of the Dungavel windfarm circuit, which is scheduled to be energised after the Low Carbon Networks Funding (LCNF) period for this project. The delay in energisation of this circuit was only due to the change in the ownership of the windfarm. This project did not fully quantify the additional headroom in the 33kV cable circuit as the actual thermal impact will appear when all 33kV circuits operate under sustained maximum generation conditions. Under a newly registered Network Innovation Allowance (NIA) project, SPEN is consequently planning to carry out further data analyses on the cable temperature profiles for a 12-month period after all the 33kV circuits have been energised.

Lessons Learnt for Future Projects

This project provided valuable lessons learnt from the implementation of the DTS and DCR systems. The key learning points are as follows:

- The installation of the optical fibre cable and micro-ducts in the centre of the trefoil cable arrangement is an effective approach for measuring the surrounding temperature of the cable, as this location can provide the closest temperature to the cable core, whilst the risk of damage to the micro-duct and optical fibre cable is relatively low.
- The quality control is an important consideration during installation in order to avoid the need for access to the ducts and optical fibres after its completion.
- The length of the installed optical fibre cable is longer than the associated power cable as additional fibre may be coiled up for calibration purposes or as spare. This additional fibre length should be deducted from DCR calculation.

- The initial data analysis of the cable temperature profiles showed that the fibre temperature, representing the cable's surrounding temperature, reaches 40 °C during highest loading conditions. Although the cable core temperature is higher than the fibre temperature, initial indications suggest that there could be still headroom to reach the 78°C maximum permissible temperature. This is subject to further assessment for at least a 12-month period after the Dungavel windfarm is commissioned in the third quarter of 2015.
- The temperature profile of a power cable is not flat and varies at different locations along the cable route, depending on the proximity to other circuits, surface type and depth of burial.
- In order to ensure that third party devices comply with IT security requirements and that the vendors understand them, early IT engagement is required.
- It is important to have a real-time, end-to-end diagnostics system in place to identify any source of error in the monitoring or communication equipment and remedial actions.

The following significant issues were encountered in the course of project:

- The delay in commissioning of the Dungavel windfarm circuit did not allow assessing the full impact of the DTS system within the lifetime of this project.
- Integration of third party equipment, which can be considered as "untrusted" to the SPEN main IT network.
- The DTS equipment uses a different communication protocol from the protocol used in SPEN's network.
- The loading of the West Browncastle windfarm circuit was not available for DCR calculation due to communication issues between the transducer and the RTU.

Under a newly registered NIA project, SPEN is planning to investigate the requirement for application of a cable temperature monitoring system in an Active Network Management system (ANM) to control the output of the generators based on real-time cable ratings.

Planned Implementation

The results and learning from this project demonstrated that both SPEN and windfarm connection customers could benefit from deploying a real-time cable temperature monitoring system. Scottish Power Energy Networks plan to conduct a new project under the NIA funding mechanism to prepare DTS and DCR systems for full business adoption. The new NIA project has been registered as "Enhanced real-time cable temperature monitoring" (NIA_SPEN0003). The following developments have been considered in this new NIA project:

- Data analysis of a 12-month period
- Requirements for integration of DTS and DCR systems into an Active Network Management (ANM) system architecture
- Policy documents and technical specifications for future DTS and DCR systems for Business as Usual (BaU) application

In addition, the implemented cable temperature monitoring system can be further enhanced by:

- Deploying for fault location application

- Defining ownership of the system and the required maintenance
- Installation of micro-duct during power cable installation
- Deployment of independent temperature sensors at possible cable hot spots

Facilitate Replication

The cable temperature monitoring system trialled in this project is completely replicable. The knowledge required to replicate the real-time cable temperature monitoring system includes:

- DTS system design methodology
- DTS system equipment specifications
- Optical fibre cable and micro-ducting installation methodology
- IT and telecommunications expertise
- Cable thermal modelling expertise
- Cable rating standards, technical papers and presentations

The products required to replicate the real-time cable temperature monitoring system can be categorised as follows:

- Monitoring equipment
- Communications and IT equipment

The services required to replicate the DTS system may be delivered by different organisations listed below:

- the DNO (or consultancy acting on the DNO's behalf)
- the monitoring equipment supplier
- the DCR thermal modelling provider
- micro-ducting and optical fibre installation provider

The following points of contacts are also available for any query with regard to replication of the DTS and DCR systems:

- Geoff Murphy, SP Energy Networks (Geoff.Murphy@sppowersystems.com)
- David Ruthven, SP Energy Networks (DRuthven@scottishpower.com)

1 Project Background

Three windfarms are scheduled to connect at 33kV to East Kilbride South 275/33kV substation in an area where there is significant windfarm activity. In order to minimise costs the three cable connections will share a common trench for the initial 10.7km length from the substation. Given the close proximity of the three 33kV windfarm cable circuits each has been de-rated to 32.2MW, based on standard design principles.

Two of the three windfarm developers have subsequently asked about the prospect of increasing their generation capacity in the future and if any spare headroom capacity might be available.

The project funding will include for the installation of micro ducting with optical fibre for all power circuits, associated Distributed Temperature Sensing (DTS) schemes, determination of real time thermal ratings for the conductor cores, monitoring and analysis to assess spare capacity.

The full Project Registration Pro-forma is given in Appendix A.

1.1 Summary

Three windfarms are to be connected at 33kV to East Kilbride South 275/33kV substation in an area where there is significant windfarm activity. In order to minimise costs the three cable connections will share a common trench for the initial 10.7km length from the substation. This shared cable route has been influenced by the need to ensure thermal independence from an existing adjacent 275kV cable that supplies Whitelee Windfarm. Each windfarm cable connection is made up of three single core cables laid up in trefoil. Given the close proximity of the three 33kV windfarm cable circuits each has been de-rated to 32.2MW.

Two of the three windfarm developers have subsequently asked about the prospect of increasing their generation capacity in the future and if any spare head room capacity might be available. The installation offers a rare opportunity to consider the dynamic ratings for three parallel adjacent cable circuits and the prospect for a future trial of active network management for distributed generation (DG), with a view to accommodating further renewable generation without network reinforcement.

The project funding will include for the installation of micro ducting with optical fibre for all power circuits, associated Distributed Temperature Sensing (DTS) schemes, determination of real time thermal ratings for the conductor cores, monitoring and analysis to assess spare capacity.

1.2 Problem

As the UK transitions towards a low carbon economy it is envisaged that there will be an increasing number of DG connection requests in areas where there is little or no spare network capacity to connect them based on traditional assessment methodology. Dynamic cable ratings may offer the prospect of further network capacity being available without the need for network reinforcement.

The traditional 'unconstrained' capacity offered to a renewable developer is calculated by using established technical considerations and operational scenarios that neglect the fact that power from renewable sources is inherently variable and hence there will be many periods when assets are not fully utilised and high cable operating temperatures do not materialise. The project will help to optimise circuit loading by using actual rather than estimates of real time thermal conditions.

1.3 Solution

The ideal location for the temperature measuring fibre optic is within the conductor this, however, is problematic on many fronts. Consequently, the optical fibre phase tends to be installed along the outside of the cable sheath. For cables laid in a trefoil arrangement the optimum location is in the centre of the three cables. However, there is the real prospect that the fibre might get crushed or damaged during installation or operation due to cable movement. For the installation under consideration the single core power cables will be installed in ducts with a resultant central gap which can accommodate a protective micro duct into which optical fibre can be blown.

2 Scope and Objectives

The scope of the project is to determine dynamic cable ratings for three cable circuits (3 - 33kV) and assess the impact the renewable generation from the three windfarms will have on these circuits. From this analysis the prospect of further network capacity being available will be determined.

This project will help inform future cable rating calculations for other projects which could negate or postpone the requirement for upgrading/reinforcing the Distribution system.

The full Project Registration Pro-forma is given in Appendix A.

3 Success Criteria

The project would be deemed successful if:

1. The temperature can be monitored across all three cables along the full cable route being monitored
2. Dynamic cable ratings are determined with associated wind generation output
3. Available headroom capacity can be determined for the three windfarm cable circuits

The full Project Registration Pro-forma is given in Appendix A.

4 Details of Work Carried Out

The project involved the installation of a DTS fibre optic system concurrently with the installation of the underground power cables of four windfarms supplied at 33kV from East Kilbride South substation, namely Dungavel, Calder Water, West Brown Castle and Ardoch & Over Enoch windfarms. Three out of the four sharing a trench for the first 10.7km of their route, and they are also in close proximity to two existing Whitelee windfarm 275kV cables.

The following steps were considered for implementing the real-time cable monitoring system:

- Selection of the most appropriate technology for monitoring cable temperatures
- Identification of trial sites for the DTS technology and equipment specification
- Carrying out of procurement and tender evaluation
- Design of the system architecture, the communication system and the thermal models
- Installation of the DTS equipment and optical fibres
- Factory acceptance tests, commissioning and site acceptance tests
- Data gathering and system performance analysis
- Validation of the monitored optical fibre temperatures using independent sensors

The monitoring system of the new windfarms required optical fibres to be laid along the full length of the 33kV circuits, encased in micro-ducts. The gap in the trefoil formation of the 33kV cables was chosen as the optimum position for the micro-ducts and thus the optical fibres.

Since the proposed DTS system monitors the temperature of the optical fibre and not that of the 33kV cables themselves, appropriate algorithms and thermal modelling was considered in order to accurately calculate the DCRs of each of the cables. The DTS system monitors the optical fibre temperatures at 30-minute intervals for every 1m of the optical fibre. The DCR algorithms are also run every 30 minutes upon receiving the updated fibre temperature data.

The DCR methodology is based on an electrical-thermal analogy model, where the thermal characteristic of each layer between the optical fibre and the power cable core is modelled. The DCR algorithms were designed according to IEC 60853 and IEC 60287 and can take into account specific environments and different cable constructions and sizes.

In order to boost the confidence in the DTS system, the optical fibre temperature measurements were validated by using independent temperature sensors, Tinytags, at two different locations.

4.1 Justification of the Planned Approach

4.1.1 DTS technology: a solution for real-time cable temperature monitoring

The temperature profile along a cable circuit is not constant and varies depending on the various surrounding conditions in different sections of the cable circuit. Type of soil, proximity to other cable circuits, type of ground surface, backfill materials and depth of burial are some of the parameters that may affect the heat dissipation level of a cable. For the purpose of monitoring the temperature of a cable circuit, therefore, it would be essential to have complete thermal visibility along the cable route.

Distributed Temperature Sensing (DTS) is a proven methodology used in different industries to monitor the thermal conditions of various types of equipment. A DTS system uses optical fibres as temperature sensors and monitors a continuous temperature profile along them. DTS methodology can be used for monitoring the temperature over a long distance, whilst being unaffected by electromagnetic interference. These specifications of the DTS system make it an appropriate technology for monitoring the temperature of the full length of power cables.

Accurate real-time temperature monitoring of power cables could lead to optimal asset utilisation. Traditionally, the thermal rating of a cable is determined based on conservative assumptions to protect the assets against the worst case, but rare, conditions. Deploying a DTS system can provide full thermal visibility along the cable on a real-time basis. Therefore, the loading of the cables can be controlled based on the actual real-time carrying capacity. The unlocked cable circuit capacity due to actual real-time cable ratings, as opposed to assumed ambient temperatures and generic estimations of ratings, can defer or negate the need for costly network reinforcement and allow for the timely connection of renewable generation.

4.1.2 Real-time temperature monitoring: Potential solution to unlock network headroom for wind power integration

Three new windfarms were scheduled to connect to East Kilbride South (EKS) 275/33kV substation via 33kV cable circuits. As initially planned, these cable circuits share a same trench in part of their route to associated wind farms and they are also located in the vicinity of an existing 275kV cable connected to another windfarm in the area. Consequently, based on common industry standard approach, they are rated to consider the mutual thermal effects that these cable circuits may have on each other.

Two of the three windfarm developers expressed their interest in lifting those constraints and increasing their generation output in the future, if any spare headroom capacity might be available. Therefore, SPEN suggested monitoring the actual temperatures of the 33kV cables by using a DTS system and applying Dynamic Cable Rating (DCR) algorithms in order to ascertain any spare capacity. A DCR system could then have the potential to be integrated into an Active Network Management (ANM) scheme to control the output of the windfarm based on the actual real-time network capacity.

Temperature variation of a cable in response to load change is not immediate due to the thermal time constant of the cable. In other words, the temperature of the cable does not change immediately as a result of a step change in cable loading. The power outputs of the windfarms are also very intermittent, i.e. windfarms do not generate a constant power up to their rated output. Therefore, based on the stochastic nature of the windfarm outputs and thermal time constant of the cables, potentially, the real-time carrying capacities of the cable circuits are higher than the "continuous" thermal rating recommended by standard practices. The DTS system is an enabler for the demonstration of this idea by providing full-length real-time thermal visibility of the cable circuits.

The DTS system relies on the temperature of the optical fibre; if cable circuits are not already fitted with a built-in optical fibre, the application of a DTS system requires installation of fibre along the power cable. In this project, the installation of the 33kV windfarm power cables were at an early stage, therefore, the application of a DTS system was identified as a timely and feasible solution, which could be implemented at the same time as the power cable installation.

4.1.3 Alternative approaches for cable temperature monitoring

Three alternative approaches to the method used in this project were identified as follows:

Modelling approach: This approach only relies on the desktop analysis of the thermal model of a cable circuit. As direct (or indirect) measurements of the cable core temperature do not take place in this approach, a complete and detailed thermal model for every section of the cable circuit should be created. The accuracy of approach based solely on modelling is very likely to be affected by some of the time-varying parameters of the thermal model, e.g. soil temperature, moisture of soil, and thermal effect of the adjacent cables. The modelling approach may be suitable for specific case studies to identify potential thermal bottlenecks along the cable circuit. Nonetheless, due to a potential lack of accuracy of the modelling approach, this method may not be reliable enough for day-to-day real-time operation of the cable circuits, in particular windfarm cable circuits, where the cable loadings are very intermittent.

Retrofitted sensor application: One of the solutions to improve the accuracy of the modelling methodology is the use of retrofitted sensors. Temperature sensors can be retrofitted in different locations which are identified as potential thermal bottlenecks along the cable. Although this approach is an improvement compared to the approach based on solely modelling, there is still a lack of full thermal visibility along the cable circuit that can affect the confidence in this methodology for real-time operation.

Application of cables with built-in optical fibre: Power cables with built-in optical fibres can be used in a DTS system. This type of cable gives temperature measurements closer to the conductor core. However, they introduce increased difficulties in optical fibre jointing and can also suffer from greater optical fibre losses. The other drawbacks of using this type of cable include limited suppliers in the market, longer time required for procurement and higher costs compared to normal power cables.

4.2 Project Location

This project initially aimed to implement a dynamic cable rating system for three 33kV windfarm cable circuits connected to East Kilbride South substation in South Lanarkshire, Scotland. These three windfarms were Dungavel, Calder Water and West Browncastle. As the project was being scoped, however, a fourth windfarm development was scheduled for connection, the Ardoch & Over Enoch windfarm, whose 33kV circuit was laid partly in the same trench as the other three windfarm 33kV circuits. In order to provide thermal visibility for all the circuits in the shared trench, the Ardoch & Over Enoch circuit was also included in this project. Table 1 outlines general information about the aforementioned windfarms. Locations of these windfarms are also shown in Figure 1.

Table 1: Windfarms considered in this project

Wind farm	Developer	Voltage	Rated Output
Dungavel	E.On	33kV	29.9MW
Calder Water	Community Wind Power	33kV	39.0MW
West Browncastle	Falck Renewables	33kV	30.0MW
Ardoch & Over Enoch	Velocita	33kV	11.5MW

Figure 1: Windfarm locations (www.renewables-map.co.uk, accessed 09 March 2015)

Due to limitations in acquiring separate routes for each cable circuit and also for reducing the installation cost, the three dedicated 33kV cable circuits connecting the Dungavel, West Browncastle and Calder Water windfarms share a trench for the first 10.7km of their length. The cables then split into two subsequent trenches, one leading to Dungavel windfarm for a further 10.7km, and the other one heading towards West Browncastle and Calder Water windfarms for around 2.7km. Figure 2 shows the detailed cable routes of the three windfarms. For the first leg out of East Kilbride South substation, approximately 0.72km, the Ardoch & Over Enoch 33kV circuit was also laid in the common trench along the other three 33kV circuits.

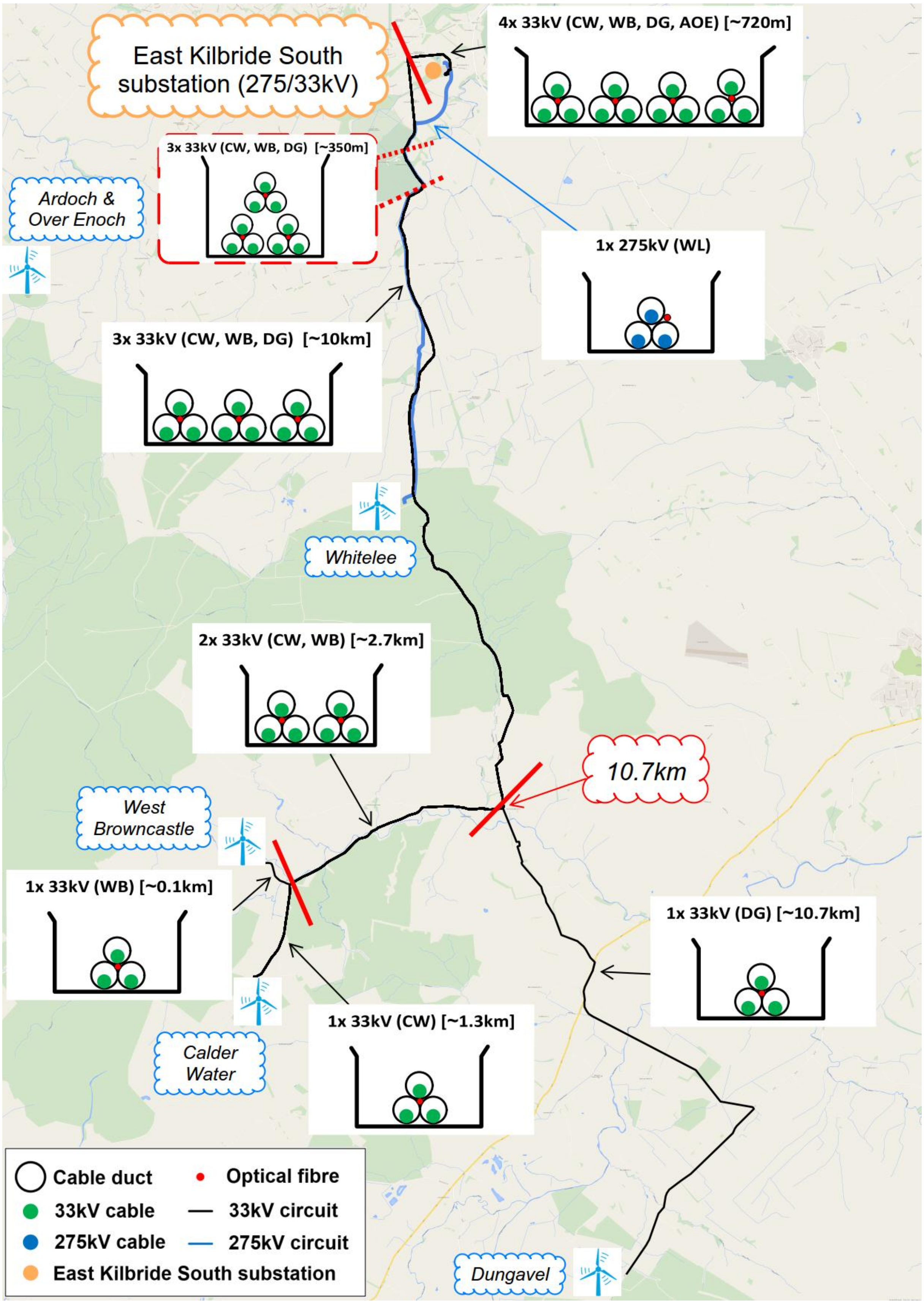

Figure 2: Windfarm cable routes, shared trenches and laid cable configuration

For each of the Dungavel, West Browncastle and Calder Water windfarm circuits, three 33kV single core 630mm^2 XLPE Cu cables were installed in their individual ducts, in trefoil formation. In general, placing cables in ducts limits heat dissipation and consequently limits their thermal rating. Typically, for 33kV 630mm^2 Cu cables in ducts, the continuous rating is 40MVA during wintertime and 37.7MVA during summertime. However, due to the sharing of trenches and being in thermal zone of adjacent circuits, each of these circuits was rated to 32.2MW (summer rating) to avoid excessive heat exchange and cable overheating.

For the Ardoch & Over Enoch windfarm, three 33kV single core 240mm^2 XLPE AL were again laid in separate ducts, in trefoil formation. Typical winter and summer continuous ratings for this cable type are 21.20MVA and 20.40MVA, respectively.

There are two Whitelee 275kV circuits, which run in the proximity of the 33kV circuits. The Original Whitelee circuit1 comprises three 275kV single core 1,000mm^2 XLPE AL cables laid in a ducted 180/160mm trefoil configuration and was the subject of previous temperature monitoring.

4.3 Trialling Methodology

The following steps were considered for implementing the real-time cable monitoring system:

- Selecting the technology for monitoring cable temperatures
- Identifying the trial sites for the DTS technology and preparing equipment specifications
- Carrying out of procurement and tender evaluation
- Designing of the system architecture, the communication system and the thermal models
- Installation of the DTS equipment and optical fibres
- Factory acceptance tests, commissioning and site acceptance tests
- Data gathering and system performance analysis
- Validation of the monitored optical fibre temperatures by using independent temperature sensors

In the following sections the detailed work carried out in each of the above step is explained.

4.4 Methodology for Selecting the Technology for Monitoring the Cable Temperature

4.4.1 Cable thermal ratings calculation method – Normal practice

SPEN, and other UK DNOs, follow IEC 62087[1] and Engineering Recommendation P17 (ER-P17)[2] as the main standards for cable thermal rating calculations. Based on these standards, EA Technology Ltd has developed an Excel-based tool, which is called CRATER and is used by most of the UK DNOs to calculate the thermal ratings of cable circuits laid in different conditions. According to IEC 62087, and as considered in CRATER, the cable thermal ratings depend on various factors such as:

- Cable thermal characteristics
- Installation and laying methodology e.g. laying configuration, ducted or direct-buried

[1] IEC 62087: "*Electric Cables – Calculation of the Current Rating*"
[2] Engineering Recommendation P17 (Part 1, Part 2 and Part 3): "*Current Ratings for Distribution Cables*"

- Soil temperature and ground thermal resistivity
- Loading conditions

Based on ER-P17, some of these factors are assumed to be constant along the length of the cable, e.g. the soil thermal resistivity is assumed to be 1.2 K.m/W. However, different values may be assumed for other parameters to reflect seasonal variations e.g. ground temperature is assumed to be 10^{o}C for the winter period and 15^{o}C for the summer period.

In reality, these factors may vary along the cable route and thermal pinch points might give rise to a non-flat temperature profile. Although correction factors can be applied to allow for variations in the conditions assumed for the calculation of the thermal ratings, it is evident that monitoring the actual temperatures of the cables and their surroundings can result in an accurate determination of the cable thermal ratings.

4.4.2 Suitability of the DTS technology

In order to de-risk the success of this project, it was decided that a well-established technique should be deployed for monitoring the temperature of the underground cables. Furthermore, the technique would have to be as less intrusive of the power cables as possible, practical, feasible and able to provide a continuous profile of the temperature over long distances with high accuracy. DTS was considered a suitable solution that met the above criteria.

By laying optical fibres along the whole length of each windfarm circuits and using DTS technology, the hot spots along the cable route in different terrain types, with various soil thermal resistances, backfill materials and depths of installation can be identified. River and road crossing sections or proximity to other forms of land could also be analysed.

An important reason that DTS was deemed appropriate for the purposes of this project was that the associated windfarms were, at the time, new developments, so there was a clear opportunity to lay optical fibre cables as part of the 33kV underground cable installation. Had the windfarms been built prior to the requirement for monitoring the cable temperatures, laying the DTS optical fibres would require excavating along the cable routes which would probably have been impractical and prohibitively expensive.

The optical fibre temperature reflects the thermal conditions surrounding the cable. This can be used together with equivalent thermal models of the cable to determine the temperature of the cable conductor core. Dynamic cable ratings of the cable can be then calculated based on the IEC 60287 standard and using real-time cable core temperatures.

As mentioned before, the 33kV windfarm cables were laid in a common trench, with three out of the four sharing it for the first 10.7km of their route, and also close to an existing Whitelee 275kV cable. The DTS system would then be able to reveal information about the thermal interactions between all of these cables.

4.4.3 Principles of operation of the DTS system

A DTS system works by sending a laser light pulse down the optical fibre and collecting the temperature dependant backscattered light. According to Raman Scattering principles – see Figure 3 – the backscattered light contains two spectral components[1]:

i. Stokes component – This component has a higher wavelength (lower energy) than that of the original optical pulse and has a temperature independent intensity
ii. Anti-Stokes component – This component has a lower wavelength (higher energy) than that of the original optical pulse and has a temperature dependent intensity

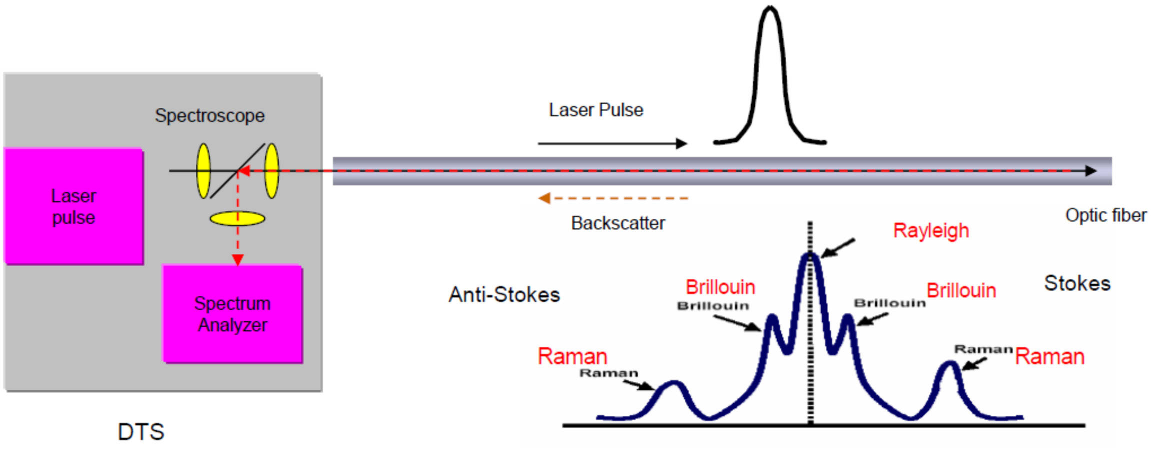

Figure 3: DTS operation and light signals

The method that a DTS system uses to measure the temperature is based on the Anti-Stokes to Stokes ratio of intensities in conjunction with the time of flight of the optical pulse to determine the temperature of the optical fibre at a given point.

4.4.4 Other DCR calculation methodologies trialled in the UK

Northern Powergrid has also trialled a methodology for calculating dynamic thermal rating of cable circuits as part of the Tier 2 Low Carbon Network Fund (LCNF) project Customer Led Network Revolution (CLNR). The methodology used in CLNR relies on modelling and desktop estimations of the underground cable thermal conditions. As there is no actual temperature monitoring of the cable or its surroundings, this methodology requires detailed thermal modelling of the complete cable route, e.g. laying information, ground surface conditions, laying depth, proximity to other cables and laying method for the total cable route.

The main downside of this approach is its reliance on a purely modelling approach with no real-time temperature measurements along the cable route. The methodology trialled in CLNR would benefit from validation by deploying independent temperature sensors at different locations along the cable.

It should be mentioned that the DTS system, which SPEN trialled in this project, is more suitable for new cable circuits, where optical fibres can be installed at the same time as power cables.

[1] "*Distributed Temperature Sensing: Review of Technology and Applications*", Abhisek Ukil, Hubert Braendle and Peter Krippner, IEEE Sensors Journal, 2011

4.5 Methodology for Identifying Trial Sites and Equipment Specification

4.5.1 Trial sites

The 33kV cable circuits connecting the four new wind farm developments, namely Dungavel, Calder Water, West Browncastle and Ardoch & Over Enoch, to East Kilbride South substation were the trial sites for this project. These four circuits share a common trench for the first 720m out of East Kilbride South substation. Then, three circuits (Dungavel, Calder Water and West Browncastle) continue to share a trench up to around 10.7km of their route. Figure 4 shows an overview of the trial sites.

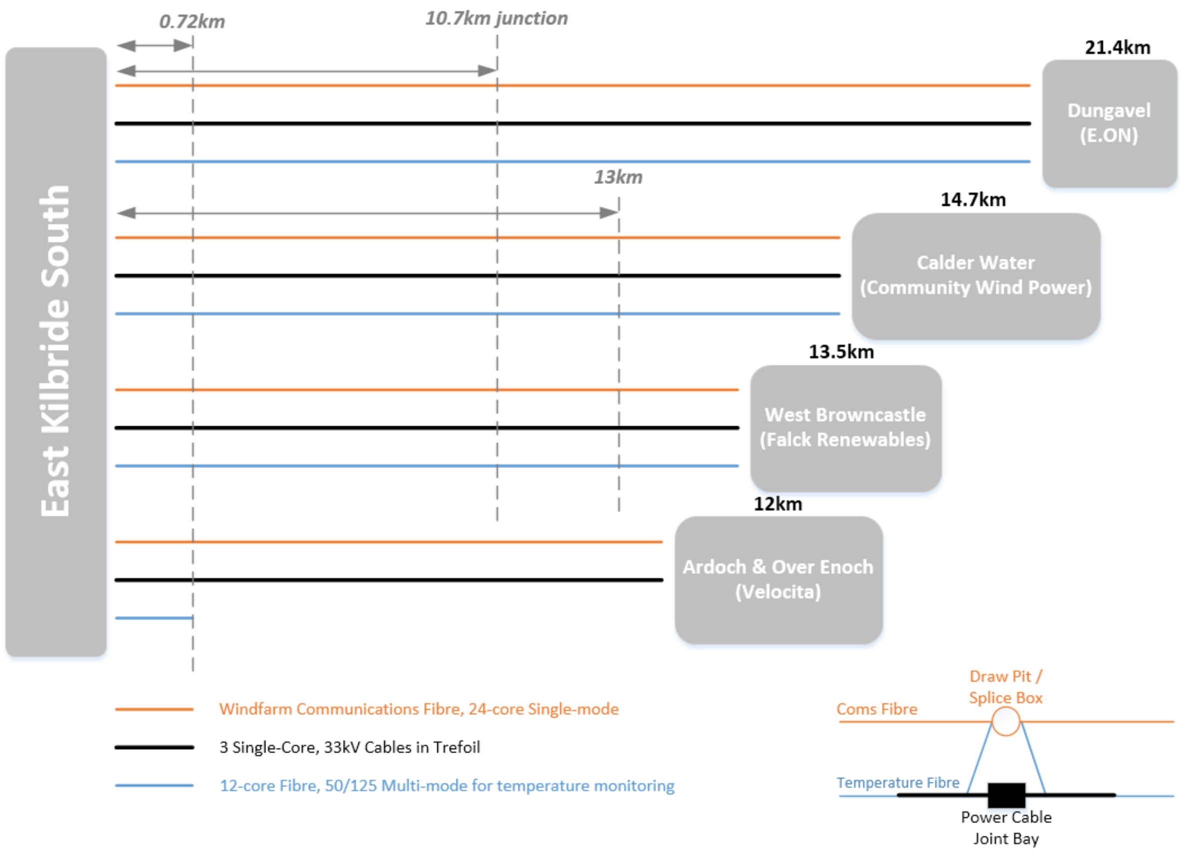

Figure 4: DTS system schematic

In order to provide a complete temperature profile of the cable circuits and investigate the mutual thermal effects between them, it was decided that the full lengths of the cable circuits, except the Ardoch & Over Enoch circuit, should be monitored by the DTS system. The Ardoch & Over Enoch circuit was not in the initial scope of project, so only the first 0.72km of its route, which is in the same trench as other circuits, was considered for monitoring in this project.

4.5.2 System requirements and equipment specification

Based on initial vendor engagement, market research and the trial site specification, general system requirements and specifications were prepared before the procurement process. A summary of system requirements is as follows:

- The monitoring system of the new windfarms required optical fibres to be laid along the full length of the 33kV circuits, encased in 14/10mm micro-ducts, with extra heavy wall thickness and low friction ribbed inner surface, suitable for blowing the optical fibres in. The optical fibres should be 12-core multi-mode 50/125μm and the micro-ducts should be continuous and without joints.

- Since the proposed DTS system monitors the temperature of the optical fibre and not that of the 33kV cables themselves, appropriate algorithms and thermal modelling were essential in order to calculate accurately the DCRs of each of the cable circuits, on a continual basis, using the DTS measurements as a data source. Visualisation of the outcomes of the DCR algorithms should be presented to engineers via graphical visualisation software that provides thermal profiling.
- The new DTS system would have to be integrated with the existing SCADA system at East Kilbride South substation and the existing PI historian servers of SPEN. As far as the SCADA system is concerned, the DTS system should be able to receive in real time available voltage, current and other measurements from the substation's existing Remote Terminal Unit (RTU).
- Additionally, as the DTS monitoring should be required for the entire lifecycle of the power cables, which typically is in excess of 40 years, it was considered likely that replacement or refurbishment of the DTS system might be required in the future. It was also anticipated that the optical fibre cabling would have to be replaced during this 40-year period and hence proper monitoring of the optical fibres' health and degradation was considered very important.
- The DTS hardware at East Kilbride South substation should include an uninterruptable power supply (UPS) system, a dedicated server with appropriate data back-up and a data logger with fixed and removable storage devices. Other necessary equipment included control cabinets, Human Machine Interface (HMI) software, optical fibre network switches, and local power supply.

4.6 Methodology for the Procurement and the Tender Evaluation

4.6.1 Methodology for procurement

4.6.1.1 Tendering process

Based on to the requirements mentioned in section 4.5.2 and the intention to integrate the DTS/DCR scheme with a future ANM scheme, the following companies were invited to tender for the project:

- LIOS technology
- Qualitrol DMS
- Sensornet
- Omnisens
- Industrial Electrical Services
- Alstom Grid UK
- BT
- HWM

LIOS Technology, Qualitrol DMS and Sensornet submitted their bids and proposed solutions in response to the tender. Post tender questions were also sent to parties to ensure compliance with the specification and to establish best fixed-price returns.

4.6.2 Contract award & basic system constituents

Following technical and commercial evaluation of tenders, Sensornet was chosen as the principal contractor. SPEN procured the following products and services from Sensornet:

- Hardware items, including:
  - a Sentinel DTS-XRM30
  - an 8-port multiplexer
  - a CL1000-M Keyboard Video Mouse (KVM) LCD console (supplied by Aten)
  - a KH 1508Ai KVM over Net switch (supplied by Aten)
  - a UPS (supplied by APC)
  - a 32U cabinet (supplied by Rittal)
  - a DC-View server and a DCR server
  - a 16-port Ethernet switch (supplied by D-Link)
- Software items, including:
  - the DCR software and thermal models for the five windfarm cables provided by Bandweaver
  - DC-View visualisation application and other DC-View services by Alquist Consulting Ltd
- Project services, such as:
  - Onsite installation, configuration and commissioning
  - Customer-witnessed Factory Acceptance Test (FAT)
  - Integrated Site Acceptance Test (SAT)
  - Client training

The 14/10mm micro-ducts and the 12-core 50/120µm optical fibres were supplied by Networx3 that also carried out their installation, termination and associated testing. In order to allow for spare optical fibres and possible waste during installation at certain locations, an additional 10% of the optical fibre length was considered during procurement.

The detailed equipment specification is given in Appendix B.

4.7 Methodology for the Cable and the Optical Fibre Installation

4.7.1 Location of the optical fibre cables

In theory, the ideal location for the optical fibre would be along the cable core in order to have very close proximity to it and provide accurate measurements without the need for extensive thermal modelling of the various layers of the cable. However, it requires deploying power cables fitted with built-in fibre. The main drawback of this approach is the limitation in replacing the fibre in case it is damaged. The cables with built-in fibre are also more expensive and potentially need more lead time for procurement compared to normal cables due to complexity of the product and limited number of manufacturers.

After comparing various options, it was decided to use the gap in the trefoil formation as the optimum position for placing the optical fibre. The bare optical fibre cables are also protected from damage during installation or operation due to cable movement by micro-duct fitted in the centre of the trefoil. The 14/10mm micro-ducts that house the 50/120µm optical fibre were installed in the gaps of each trefoil formation – see Figure 5. The micro-ducts were laid continuous and without joints, except at cable joints, along the 33kV cable duct sections.

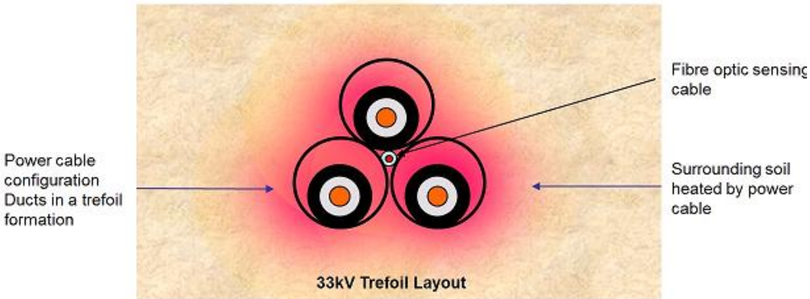

Figure 5: Duct and cable arrangement per 33kV circuit

4.7.2 Micro-duct and cable installation

The methodology used for power cable installation was based on SPEN's technical policy for the handling and installation of 33kV ducted cable circuits. In addition, a complete method statement was developed for this specific installation where the micro-ducts should be installed at the same time as the power cable duct installation, see Appendix C for the installation method statement. In order to place the micro-duct in the middle of the trefoil, the two cable ducts were placed in the trench floor followed by placing the micro-duct in the top middle of these two ducts. The third cable duct was then installed, see Figure 6.

The 33kV windfarm cables were installed in trefoil formation in 160/150mm ducts. For each windfarm circuit consisting of three single core 33kV cables, one cable was laid inside each duct. The 33kV cables were jointed every 500m.

The installation had to be executed with extreme care in order to avoid the need for access to the duct and optical fibres after its completion. This was identified as an important risk of the project that could potentially involve opening up of joint bays. In order to mitigate this risk, it was ensured that the method statement was properly communicated with the cable installation contractor.

The micro-ducts were labelled and colour coded to avoid confusion during their installation and to help identify them in the event of future maintenance, see Figure 7. The following labels and colours were used for each circuit:

- Dungavel windfarm DTS: "***EK STH GSP to DUNGAVEL W'FM – DTS***" – Red
- Calder Water windfarm DTS: "***EK STH GSP to CALDER WATER W'FM – DTS***" – Green
- West Browncastle windfarm DTS: "***EK STH GSP to WEST BROWNCASTLE W'FM – DTS***" – White
- Ardoch & Over Enoch windfarm DTS: "***EK STH GSP to Ardoch & Over Enoch W'FM – DTS***" – Purple

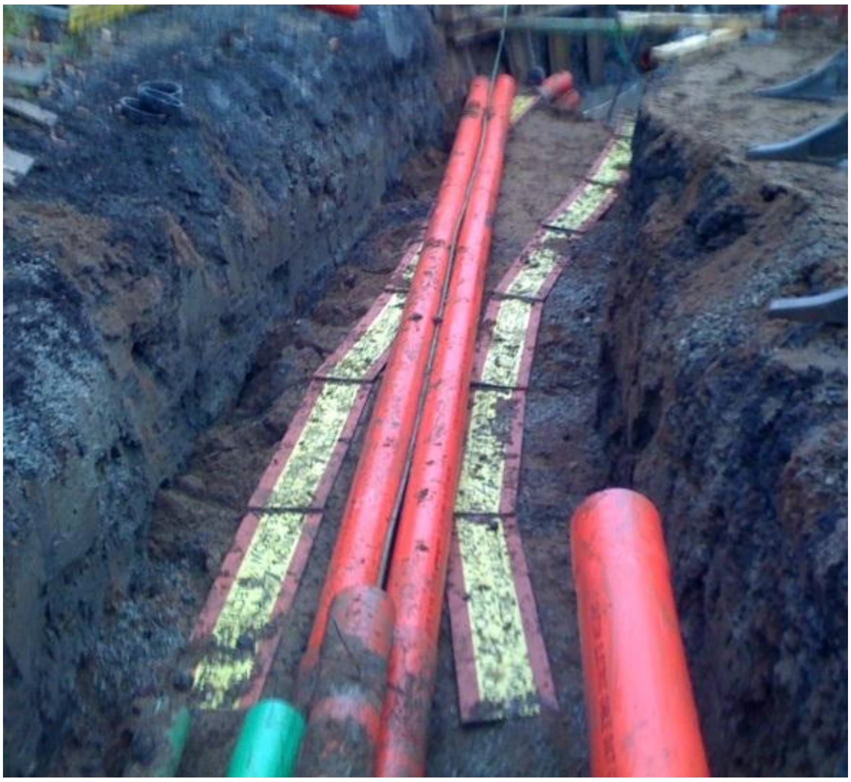

Figure 6: Micro-duct is placed on the top of the two cable ducts before fitting the third cable duct

Figure 7: Embossed micro-duct – West Browncastle (white)

Figure 8 and Figure 9 show the 33kV cables in the shared trench with micro-ducts installed in the centre of each trefoil arrangement.

Figure 8: Shared trench with all four circuits near EKS substation

Figure 9: Shared trench with three circuits

Table 2 summarises the details of each 33kV cable circuit.

Table 2: 33kV Cables and optical fibres

WF Name	Cable Type	Circuit Length	Formation	Optical Fibre Type	Optical Fibre Length
Dungavel	3 x 1c 630mm^2 XLPE Cu	10.7km	Trefoil	50/120µm multi-mode	10.7km
	3 x 1c 500mm^2 XLPE Cu	10.7km	Trefoil	50/120µm multi-mode	10.7km
Calder Water	3 x 1c 630mm^2 XLPE Cu	14.7km	Trefoil	50/120µm multi-mode	14.7km
West Browncastle	3 x 1c 630mm^2 XLPE Cu	13.5km	Trefoil	50/120µm multi-mode	13.5km
Ardoch & Over Enoch	3 x 1c 240mm^2 XLPE Al	12km*	Trefoil	50/120µm multi-mode	0.72km

* This circuit only shares 0.72km of its length with other three cable circuits. Some part of this circuit is in the form of overhead lines

4.7.3 Installation of the chambers

Chambers were installed around every 0.5km along the cable route and within 10m of the 33kV cable joint bay. They housed the telecommunication and DTS fibre joint boxes. Chambers were installed for the following purposes:

- **Joining the optical fibre cable sections:** Optical fibres need to be blown into the micro-ducts at every 2km section. Chambers were used to provide access to the end of optical fibre sections. Optical fibre sections were joined, using a fusion splicing technique, at each optical fibre joint box located in each chamber. Some of the chambers were also used for joining the windfarms' telecommunications fibre.
- **Access to the optical fibre cables for maintenance:** In case of a fibre break or for any other maintenance purposes, chambers are the main access points to the optical fibre cables.
- **Providing room for spare optical fibres:** For future optical fibre replacement, if required, spare lengths of optical fibre cables were coiled up and placed in the chambers.

Figure 10 shows one of the chambers housing the DTS fibre junction box.

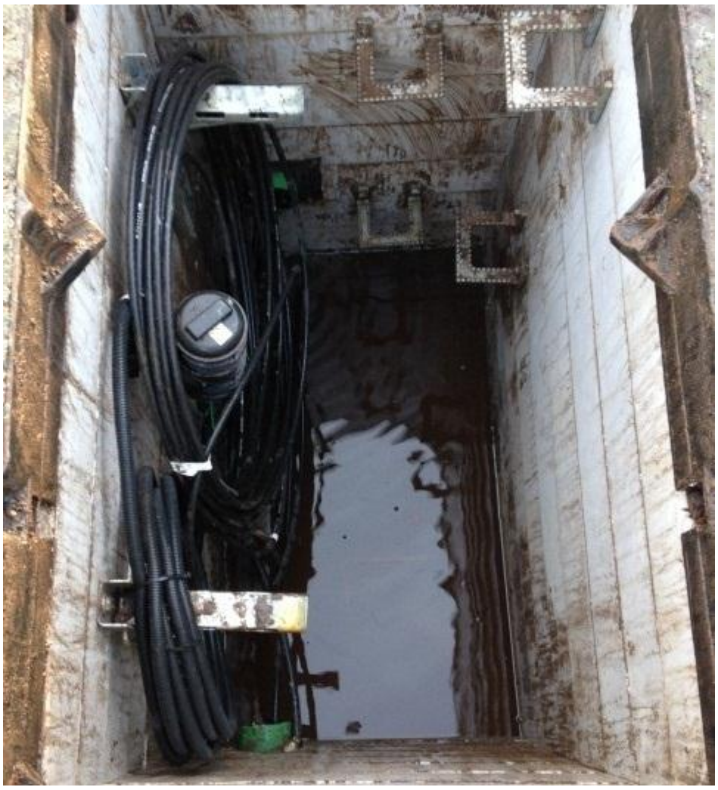

Figure 10: Chamber and DTS fibre joint box

In order to avoid additional site work, expedite the installation works, reduce the road closure time and reduce the total cost of chamber installation, it was decided to use pre-cast chambers shown in Figure 11.

Figure 11: Pre-cast chamber

4.7.4 DTS fibre installation

In order to reduce stress on the fibre and installation time the optical fibres were blown into their respective micro-ducts by utilising an Airstream Cable Blowing System (CBS) shown in Figure 12. From the blowing locations, which were chambers or EKS substation, the optical fibre was blown in either direction, thus covering the full length of the installation. It should be noted that blowing the optical fibre is generally quick, but introduces an additional length due to snaking effects, i.e. optical fibre length is greater than cable length.

Figure 12: CBS Airstream blowing head (location: EKS substation)

4.7.5 Windfarm telecommunication fibre installation

The windfarms' telecommunications 24-core fibres were laid in a quad duct as shown in the upper left corner of the shared trench in Figure 13. DTS fibre was jointed, as was the telecommunications fibre, within a jointing chamber every 2km.

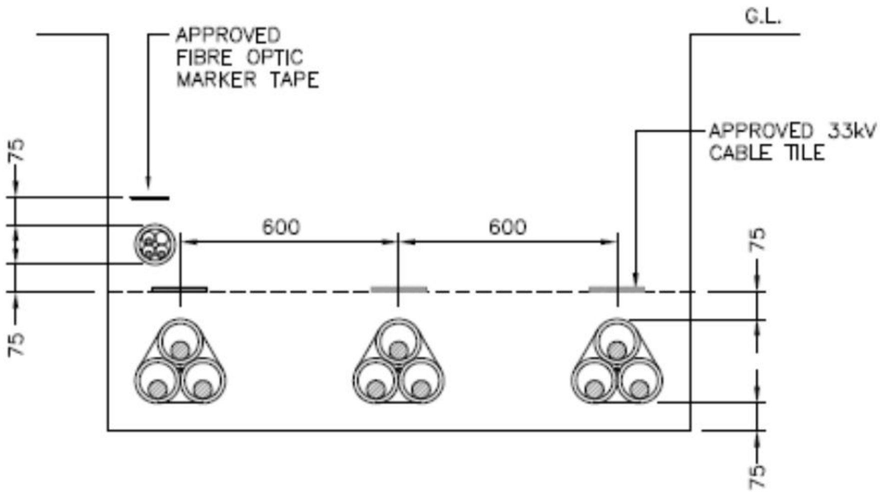

Figure 13: Shared trench cross-section, the location of the telecommunications and ducted cable in the trench

4.7.6 DTS equipment at East Kilbride South substation

At the time of the cable and optical fibre installations the four new windfarms did not have their individual substation erected, so no site could house the equipment of its dedicated DTS system. It was therefore decided to install only one DTS cabinet at East Kilbride South with all optical fibres being terminated there.

The original 275kV Whitelee windfarm cable circuit connected to EKS substation had already been fitted with a DTS system. The DTS equipment of the Whitelee cable circuit had been placed in a cabinet within the telecoms room in EKS substation. It was initially planned to install the 33kV DTS equipment in a new containerised substations at EKS substation. Due to delay in its installation, however, it was decided to replace the existing Whitelee DTS cabinet in ESK substation with a new one to house the DTS equipment of the new 33kV circuits together with the existing Whitelee 275kV circuit. For future installations it would be more appropriate to place the DTS equipment near RTUs through which voltage, current, active power and reactive power measurements of windfarm circuits are made available to DTS system.

The micro-ducts entering the substation building were protected with a 25mm steel armoured copex, from building entry up to the DTS cabinet, and were terminated and secured in the top of the cabinet. In order to terminate the optical fibres and connect them to Sensornet’s DTS system, Tyco E2000 pigtails were utilised. These pigtails are optical fibre connectors with a spring-loaded shutter, which fully protects from dust and scratches.

4.8 Dynamic Cable Rating System Architecture

4.8.1 Optical fibre connection arrangement

Two different configuration types were used for the optical fibre cables in this project:

i) Single-Ended
ii) Double-Ended

Single-Ended: In this configuration, the DTS system measures the temperature of the optical fibre cable strung from the multiplexer to the end of the cable route. Only one port of the multiplexer is allocated to the optical fibre as only one connects to the DTS equipment, i.e. the multiplexer, at one end.

Double-Ended: A double-ended channel means that the optical fibre is looped back towards the DTS system at the far end of the installation, with the first half being the outbound measurement and the second half being the return measurement. This configuration requires two ports on the multiplexer and enhances the accuracy and reliability of the DTS system by providing two measurements for each point of the power cable. In the case of a fibre break in one of the halves, the DTS can stay operational and monitor the temperature in the other half. It should be noted that the measured data is twice as long as the physical cable.

Figure 14 shows the two different fibre connection arrangements.

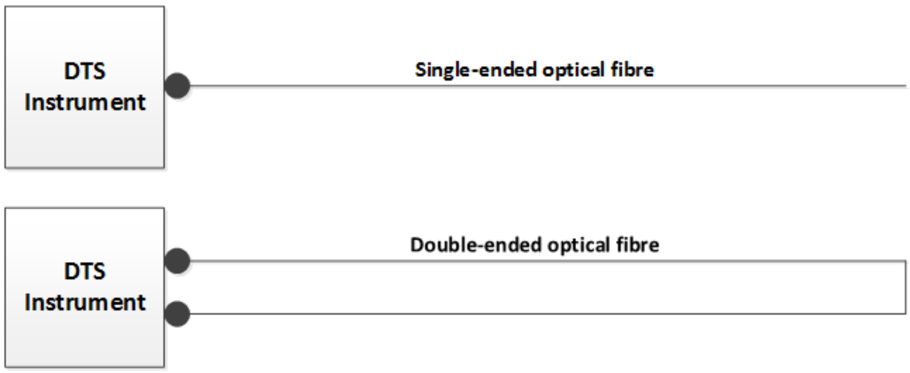

Figure 14: Types of optical fibre connection

Table 3 summarises the optical fibre connection arrangement installed for each of the windfarms.

Table 3: DTS fibre lengths and connection types at EKS substation

WF Name	Length	DTS Measurement	Parent Channel	Multiplexer Port	Sample Time
Calder Water	14.7km	Double-Ended	1	1 & 2	300s
West Browncastle	13.5km	Double-Ended	3	3 & 4	300s
Whitelee	6.2km	Double-Ended	5	5 & 6	300s
Dungavel	21.4km	Single-Ended	7	7	120s
Ardoch & Over Enoch	0.72km	Single-Ended	8	8	120s

The DTS equipment trialled in this project was capable of measuring the temperature distribution along optical fibres up to 25km in length. The Dungavel windfarm circuit is 21.4km long which requires 42.8km (2 x 21.4km) of fibre length for a double-ended connection. As double-ended connection was outside capability of the DTS equipment, it was decided to use single-ended connection for Dungavel circuit.

The DTS system monitors the optical fibre temperatures at 30-minute intervals. At the beginning of every 30 minutes, the DTS system starts with the first channel, for instance Channel 1, and measures the temperature along the optical fibre. The measured temperature data for every metre of the optical fibre are then recorded and the DTS system then switches to the next channel and carries out the same process. The installed DTS unit has an 8-port multiplexer, which allows the monitoring of the 3 double-ended and 2 single-ended optical fibres as trialled in this project.

The “parent” channels (Channel 1, Channel 3, Channel 5, Channel 7 and Channel 8) are the ones that hold the full dataset of the monitored temperature along the optical fibre, with 0.0 m being at the back of the DTS system at East Kilbride South substation. For double-ended configurations, for example Calder Water, data in Channels 1 and 2 are internally combined to produce a single file containing forward and reverse datasets. The “parent” channel data can then be split into multiple “child” zones that are indexed in the DC-View list. Each zone can represent the temperature variations in a section of the cable circuit, e.g. SPEN defined 42 zones for the Calder Water circuit on Channel 1.

4.8.2 System architecture

The DCR system consists of the DTS equipment and the workstations, which perform different functionalities. Figure 15 shows the complete system architecture implemented in this project.

The DTS workstation at East Kilbride South substation gathers the optical fibre temperature measurements. The measured data is sent via a Modbus Import server and over the SPEN network infrastructure to the DC-View and DCR servers. In addition to optical fibre temperatures, other measurements such as current, voltage and power for each circuit are received from the local RTU at East Kilbride South and transferred to the DCR server.

The DCR calculations take place at the DCR workstation. The DCR server uses the monitored temperature data together with the detailed cable thermal models – see section 4.8.4 – to calculate the cable core temperatures, the pinch point locations and the DCRs for each circuit. The results of the DCR calculations are then transferred to DC-View workstation where they are displayed via a user-friendly interface.

The calculated core temperatures, DCRs and measured values can be visualised in real-time by remote access to the DC-View workstations and via a dashboard specifically customised for this project. DCR values are also transferred to SPEN’s PI data historian using XML protocol.

The DC-View and DTS Windows-based units are configured to synchronise their real time clocks through an Internet Time Server to ensure that they maintain accuracy.

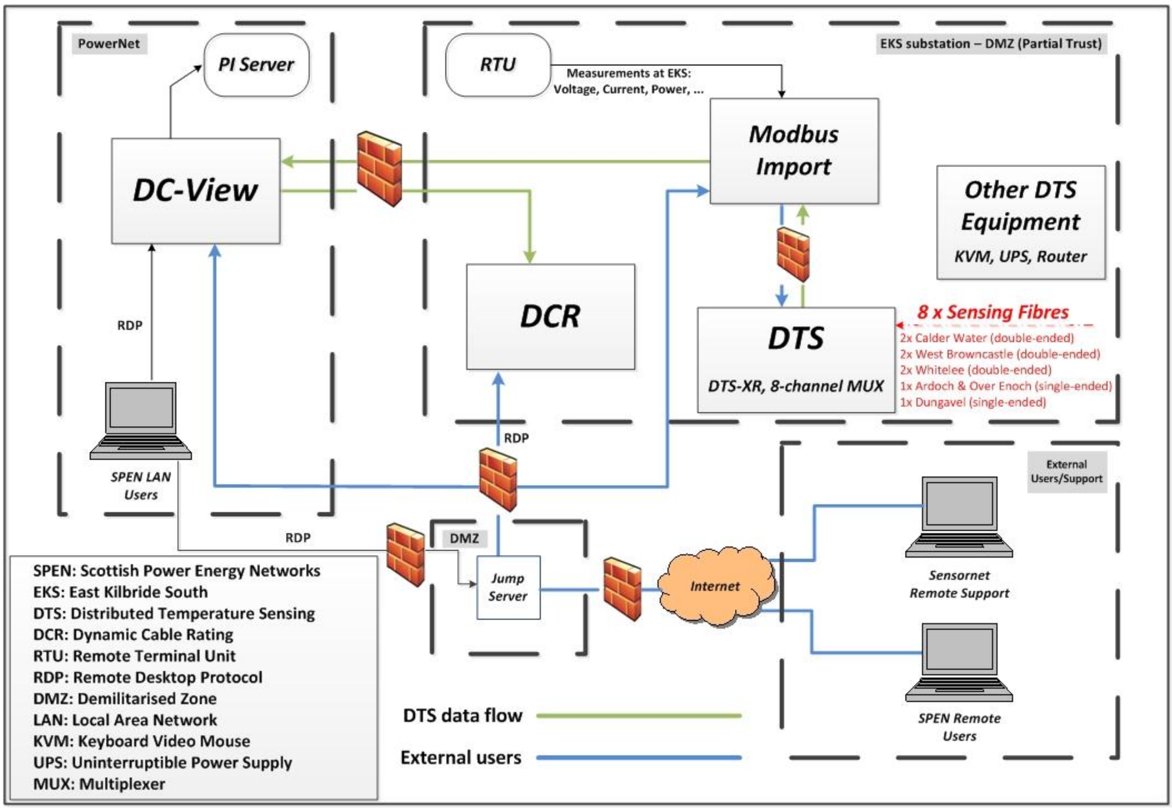

Figure 15: DCR system architecture

The system architecture and configuration of the workstations initially provided by the supplier were modified to meet SPEN's security requirements. Nonetheless, the DTS workstations to which the DTS equipment and optical fibre are attached could not be modified due to designed communication between DTS hardware and workstation. In order to mitigate the security risk that the DTS presented to the SPEN network, a local network was created between the DTS workstations and the Modbus Import, which was configured based on SPEN's security standards. This modification ensured that all communications to the main SPEN corporate network are via a managed device.

A standard supported workstation configured by SPEN was also set up for the DC-View workstation. The DC-View server was configured in Terminal Services mode that allows multiple simultaneous connections, while being hosted in the datacentre ensures that its data can be backed up regularly without issues.

In order to facilitate the remote support of a third party, a site-to-site Virtual Private Network (VPN) service was implemented between the SPEN's network and Sensornet. This connection was established through a Terminal Server (termed as Jump Server) and it was preferred that all connections to the SPEN network should be terminated at this Terminal Server and through Remote Desktop Protocol (RDP). In this way, SPEN network security is not compromised and all connections are via a central server by which all domain authentications are mandated.

4.8.3 User interface

All monitored data and calculated values can be visualised through the DC-View software produced by Alquist Consulting Ltd. DC-View is a Windows based application which is installed on a local server in the data centre and SPEN users can access it via remote desktop service. DC-View displays the following information through a user-friendly interface:

- Real-time and historical heat maps of the complete optical fibre temperature profiles of the cable circuits
- Real-time and historical calculated cable core temperatures and cable thermal ratings
- Real-time and historical loadings and voltages of the cable circuits
- Real-time and historical temperature profiles of the cables within specific zones, which are defined by the user
- Historical optical fibre temperature profiles and dynamic cable ratings
- Fibre break alarms for each circuit

Figure 16 shows the main interface window of DC-View.

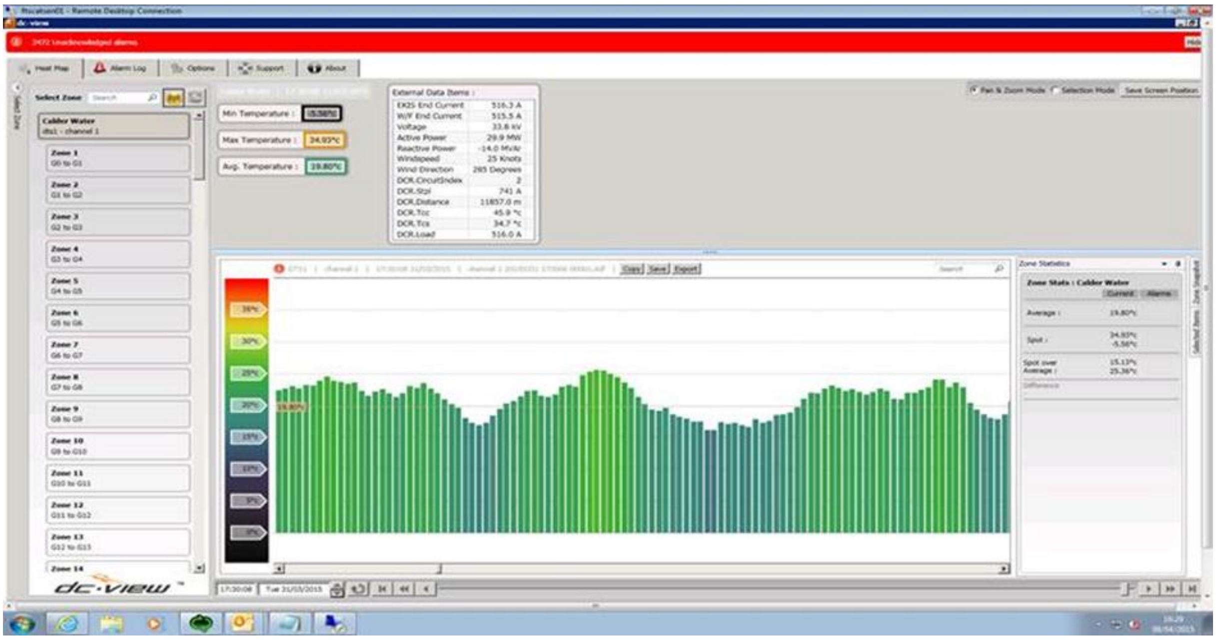

Figure 16: DC-View main interface window

4.8.4 DCR thermal modelling

The DCR software, produced by Bandweaver, uses the measured optical fibre temperatures together with thermal models of the cables to calculate the cable core temperatures and dynamic cable ratings. The DCR methodology is based on an electrical-thermal analogy model, where each layer between the optical fibre and the power cable core is modelled by a thermal resistor, a thermal capacitor and a current source. The thermal resistor represents the layer's ability to dissipate heat, while the thermal capacitor models the layer's characteristic to store heat. Figure 17 shows the electrical-thermal analogy model used by the DCR software.

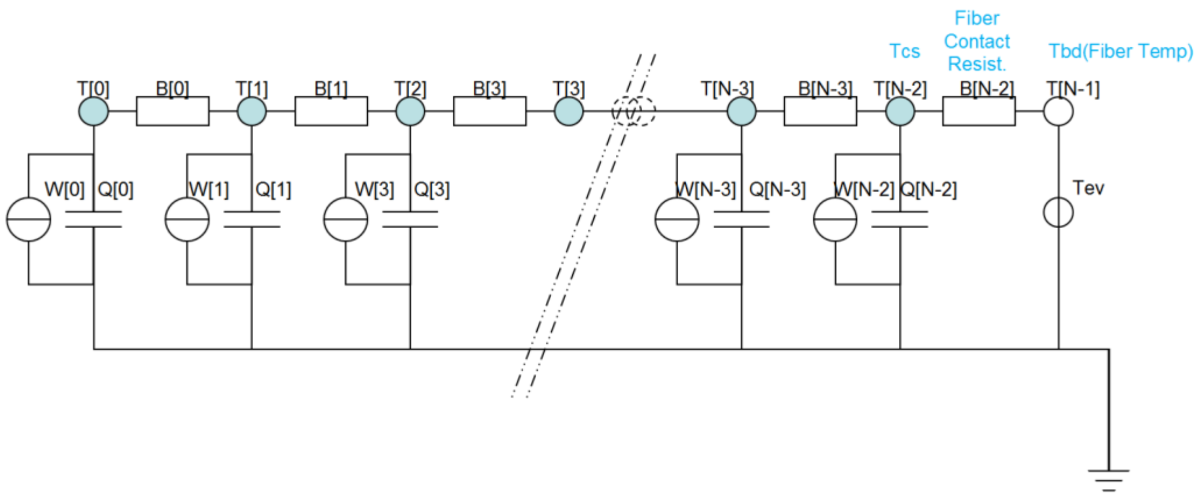

Figure 17: DCR thermal model

The DCR thermal rating algorithms, which were developed by Banweaver with intellectual property rights (IPR) belonging to this company, were designed according to the IEC 60853 and IEC 60287 standards. The algorithms are very flexible and can take into account specific environments and different cable constructions and sizes. The DCR software can calculate thermal ratings in a real-time basis and can also predict ratings over a 48-hour period. It can also be used for offline calculations to help plan operating procedures effectively without risk of exceeding the cable ratings.

4.8.5 Optical fibre length correction in the DTS system

There is extra optical fibre coiled up just outside the DTS cabinet at East Kilbride South, which was used for initial calibration purposes and is available for future calibration. This additional DTS fibre length – see Figure 18 – should be deducted from the DCR calculations to ensure that the optical fibre length is aligned with the power cable length. In order to eliminate this extra optical fibre length, a “dead zone” and a “buried conductor zone” were defined for each optical fibre circuit – see Table 4.

- Dead-zone: the length of cable which should be removed from the calculations
- Buried conductor zone: the optical fibre length which is located along the power cable

Table 4: Dead Zone and Buried Conductor Zone defined for each cable circuit

Circuit	Dead Zone	DC-View Cropped Display	Configuration	Buried Conductor Zone
Calder Water	0-94m	0-29,871m	Double Ended	94-14,856m
West Browncastle	0-193m	0-28,467m	Double Ended	193-14,207m
Whitelee*	0-225m	0-12,701m	Double Ended	225-6,303m
Dungavel	0-134m	0-10,808m	Single Ended	134-10,808m
Ardoch & Over Enoch	0-134m	0-918m	Single Ended	134-918m

* Whitelee windfarm circuit 1 had been previously fitted with DTS system. The existing Whitelee optical fibre cable was integrated into the new DTS and DCR system in this project to enhance the functionalities of the previously installed Whitelee DTS system.

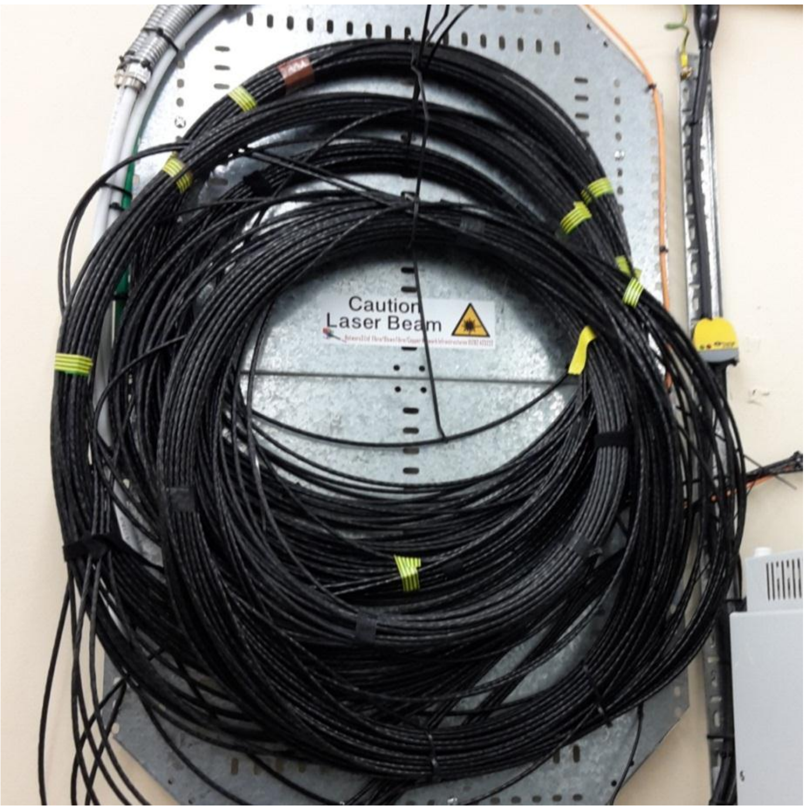

Figure 18: Additional optical fibre lengths (calibration loop) coiled up in EKS substation

4.9 Methodology for the Factory Acceptance Test and the Site Acceptance Test

4.9.1 Factory acceptance test

Prior to delivering the DTS system, a Factory Acceptance Test (FAT) of the DTS equipment was carried out at Sensornet's premises in Elstree in the presence of SPEN project staff. The system configuration that was tested was as close as possible to the final configuration at East Kilbride South, as expected at the time. The following tests were carried out on the DTS system, with all of them being successful:

- **Physical check**: This test included the physical appearance of the equipment and DTS cabinet, equipment labelling, sufficient mechanical support, appropriate earthing and wiring.
- **DTS functionality**: This test included the performance of the DTS for single-ended and double-ended configurations, optical fibre break detection and distributed temperature trace of a test optical fibre.
- **DC-View functionality**: This test included fibre break alarms, features to split total optical fibre length to different zones and a simulation of planned installation system.
- **DCR functionality**: This test included the overview of the DCR model and input data, DCR interface features and end-to-end DCR interface checks with other DTS applications and equipment.
- **Open platform communication (OPC) interface**: This test included an interface check and data exchange check between DTS equipment, the DTS workstation and Modbus.

4.9.2 Site acceptance test

Commissioning of the DTS system took place after carrying out a Site Acceptance Test (SAT) at East Kilbride South substation. Prior to the DTS SAT, an Optical Time Domain Reflectometer (OTDR) test took place to ensure that all optical fibre cabling links were properly installed.

The SAT of the DTS system was conducted in the presence of SPEN project staff and Sensornet, over a two-day period and after installation and calibration of the DTS system. The same Sensornet equipment as for the FAT was tested with the exception of the multiplexer, this time it being an 8-port multiplexer, and with the addition of the UPS system. The test procedure comprised:

- **Visual inspection**: This included checking the position of the DTS equipment in the cabinet – see Figure 20 – mechanical installation, screws and bolts, appearance and dimensions, labels, wiring and insulations.
- **Equipment specifications and settings**: This included checking the equipment specifications against those approved in the FAT and also checking equipment settings based on the initial planned settings and equipment manuals.
- **System start-up & system fault test**: This included checking power supplies to the DTS system and checking whether the DTS system will detect the multiplexer and other equipment after switching on its supply. The system's ability to notify potential system faults was also checked.
- **Fibre break test**: This included testing the capability of the DTS system to detect a fibre break and identify the fault location.
- **UPS soft shut-down & system re-start**: This test included checking the capability of the UPS to maintain power supply in the event of an outage of the main power supply.
- **Forwarding service test between the DTS and DC-View servers**: This included checking that the monitored temperature data are transferred correctly from the DTS server to the DC-View server.
- **Maximum temperature alarm test**: This test includes checking the temperature alarm for optical fibre temperatures above a pre-set maximum level. For the purposes of this test, part of the installed optical fibre cable (calibration loops) was coiled up and placed in a controlled temperature water bath – see Figure 19 – to simulate the underground temperature increase. The temperature of the water bath was increased to 40°C[1] and it was verified that DC-View generated the maximum temperature alarms.

The DTS system requires calibration to ensure the accuracy of the optical fibre temperature measurements. To do that, a similar water bath methodology to that of Figure 19, used for the maximum temperature alarm test, was used. The process included submerging the optical fibre coil into water, stabilising the water temperature above or under the ambient temperature, using the water temperature as the reference temperature and calibrating the DTS measurement to match the reference temperature.

[1] This temperature is only used for the purposes of a site acceptance test and does not reflect the maximum operation temperature of the cables

Figure 19: Water bath technique used for DTS calibration and maximum temperature alarm test

Figure 20 shows the DTS cabinet as installed at East Kilbride South substation.

Figure 20: DTS system cabinet at EKS substation

4.10 Methodology for Assigning Zones of Interest

As the DTS system measures the surrounding temperatures of the cables along their full length, it is natural that thermal conditions change along the cable routes due to changes in the following parameters:

- Ground surface type e.g. road, river etc.
- Burial depths and installation methodology (ducted or direct-buried)
- Proximity to adjacent cables
- Backfill materials

Based on these parameters, zones of interest were defined for each cable circuit, e.g. in total, 42 zones of interest were considered for the Calder Water and West Browncastle circuits. DC-View displays the temperature profile for the length of the cable laid in a zone of interest.

The zones of interest defined in this project are used to distinguish temperature profiles at the following locations:

- The length of optical fibre, which is located at East Kilbride South substation. This zone is known as a dead zone as the optical fibre is not monitoring the surrounding temperature of the cable.
- The length of cable circuits which are located in the shared trench (10.7km junction).
- The length of cable circuits where there is no thermal effect from adjacent cables.
- The parts of the 33kV cable circuits which are in the vicinity of the Whitelee 275kV cable circuit. This occurs for a certain part of the route only.
- The cable joints and chambers where the optical fibre moves away from the power cable.

4.11 Methodology for Validation of the Monitored Optical Fibre Temperature by Using Independent Temperature Sensors

In order to confirm the accuracy of the temperatures measured by the DTS system, the optical fibre temperature measurements were validated by using independent temperature sensors. A temperature sensor and data logger called Tinytag – see Figure 21 – was used to validate the variations with time of the optical fibre temperature at two different locations:

1) East Kilbride South substation: This location represents indoor temperature conditions. The Tinytag was placed next to the optical fibre cable coil just outside the DTS cabinet – see Figure 22.
2) Chamber 17: This location represents outdoor temperature conditions. The Tinytag was placed next to the Calder Water optical fibre cable coil – see Figure 23.

The results of the validation are given in section 5.7.

The Tinytags, supplied by Gemini Data Loggers Ltd, are capable of recording up to 32,000 readings of average, minimum and maximum temperatures ranging between -40^{o}C and +85^{o}C with a 0.01^{o}C resolution. This battery-powered sensor can be easily installed and secured with cable-tie very close to the optical fibres.

Figure 21: Temperature sensor and data logger, Tinytag

Figure 22: Tinytag located in East Kilbride South substation

Figure 23: Tinytag located at Chamber 17

5 The Outcomes of the Project

The outcomes of the project are outlined as follows:

1. Implementation of the DTS system for the Calder Water, West Browncastle, Dungavel and Ardoch & Over Enoch 33kV circuits.
2. Monitoring of half-hourly temperature variations of every metre of the optical fibre cables installed along the cable circuits through a user-friendly interface, DC-View, customised specifically for this project.
3. Development of transient thermal models for each of the cable circuits, which are used for estimating the core temperature of each circuit based on the corresponding optical fibre temperature.
4. Calculations of maximum core temperatures and thermal pinch point locations along the cable circuits.
5. Validation of temperatures measured by the DTS system by deploying the independent temperature sensors (Tinytags).
6. Gathering and analysis of the DTS data in conjunction with cable circuit loading data to provide learning on cable temperature profiles and causes of the thermal pinch points.

The results of initial data analysis are as follows:

- The output power of the windfarms follows a stochastic variation that may allow cable circuits to dissipate heat during high wind periods. The daily Loss Load Factors (LLF) of the Calder Water and Whitelee cable circuits from 01/01/2014 to 12/03/2015 were calculated and the results showed that for 80% of the time the LLF of the cable circuits can be below 0.5. This suggests a dynamic rating, rather than a continuous rating, could be more relevant for windfarm cable circuits. However, a DTS system should be in place to monitor the conditions and trigger the require actions to limit the cable loading when cable temperature may go beyond the permissible limits.
- The analysis of Dungavel fibre temperature data demonstrates the mutual heat impact from adjacent cables. The surrounding temperature of the Dungavel circuit increased by around 8°C during the period when other circuits carry the rated output power of the windfarms. It should be noted that the Dungavel windfarm circuit is not energised yet and temperature variations seen along this circuit are largely due to thermal impacts of adjacent circuits.
- The maximum recorded fibre temperature is for a day with a high LLF and reaches to around 40.0°C. Although we expect that the core temperature should be higher than the fibre temperature, it seems there could be headroom before reaching maximum permissible temperature (78°C). SPEN is planning to investigate this further by carrying out data analysis on a 12 month period of data when all the 33kV circuits have been energised under sustained maximum generation conditions
- The location of thermal bottlenecks along the cable circuits seem to remain almost unchanged. That suggests using higher rated cables or using back-fills for better heat dissipations at some locations may help to increase the overall thermal rating of the cable circuits.
- The causes of thermal bottlenecks identified along the cable circuits are due to:
  1- Crossing point with the Whitelee 275kV cable circuit
  2- Change in depth of burial, for example before and after crossing a river
  3- Thermal effects from adjacent cables and low heat dissipation conditions, e.g. at the locations where the cable circuits are placed in a pyramid formation
- The comparison between an independent temperature sensor and the fibre temperature

for a 10-day period validated the accuracy of the DTS system at two different locations along the cable route.

5.1 Overview of the Outcomes of the Project

The outcomes of this project are outlined as follows:

1. Installations of the DTS system for the Calder Water, West Browncastle, Dungavel and Ardoch & Over Enoch 33kV circuits.
2. Monitoring of half-hourly temperature variations of every metre of the optical fibre cables installed along the cable circuits through a user-friendly interface, DC-View, customised specifically for this project.
3. Development of transient thermal models for each of the cable circuits, which is used for estimating the core temperature of each circuit based on real-time and historical optical fibre temperature measurement.
4. Calculations of real-time maximum core temperatures and thermal pinch point locations along the cable circuits.
5. Validation of DTS temperatures measured data by deploying the independent temperature sensors (Tinytags).
6. Gathering and analysis of the DTS data in conjunction with cable circuit loading data to provide learning on cable temperature profiles and causes of the thermal pinch points.

In the following sections the detailed outcomes of the project and the results of the analyses of the DTS data, recorded between 01/01/2015 and 18/03/2015, are presented. The DTS data used in this section include half-hourly optical fibre temperatures for every metre of the Calder Water, West Browncastle and Dungavel windfarm circuits. Also, the loadings of the Calder Water and Whitelee windfarm circuits were obtained from SPEN's data historian (PI), from 01/01/2014 to 12/03/2015, and used in the analyses. Due to communication issues between RTU and transducer, which were only recently resolved, the historic loadings of West Browncastle are not available to be presented in this report. It should be also noted that the Dungavel windfarm circuit loading is not available as this circuit is scheduled to be energised in the third quarter of 2015. Nonetheless, the fibre temperature data for 10.7km (out of 21.4km) of Dungavel circuit is available and presented in this report.

For research purposes a dataset including fibre optic temperature and the loading of the Calder Water is provided in Appendix D.

5.2 Outcomes of the DCR Calculation Engine

The DCR workstation located at East Kilbride South substation hosts the dynamic cable temperature calculation engine. For estimating the cable core temperatures, DCR uses the algorithms and the modelling methodology described in section 4.8.4 along with the real-time and historical optical fibre temperatures transmitted from the DTS system. The results of the calculations are available through a dashboard customised specifically for this project.

Figure 24 shows the front page of DCR dashboard interface. The following features are available through the DCR's dashboard interface:

- Summary of the loading, maximum optical fibre temperature and maximum cable core temperature for all cable circuits.

- Alert notifications when the temperature of the cable exceeds the design set points.
- Plots of historic cable temperature variations along with the associated circuit loadings.
- Calculations of Short-Term Permissible Loading (in Amps)based on the latest cable thermal conditions.
- Illustration of the radial temperature distribution from the optical fibre to the cable core.
- Illustration of system architecture and the cable sections with associated optical fibre configurations

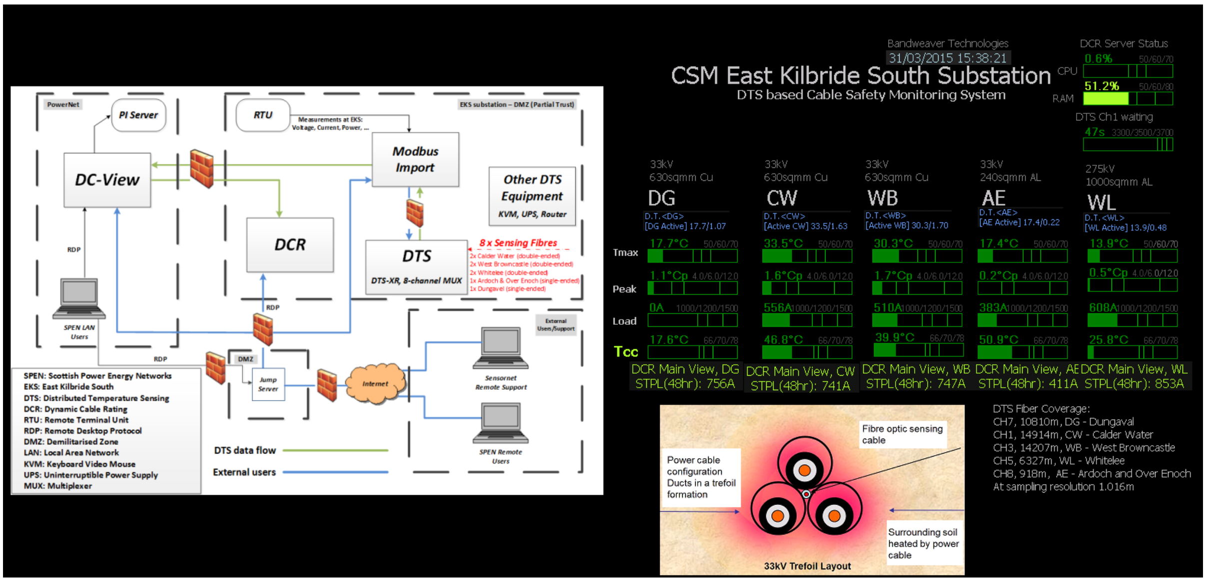

Figure 24: DCR dashboard at EKS substation

Figure 25 shows an example of the DCR interface feature reporting the historic calculated data. In this example, the variations of the maximum cable core temperature (T_{cc}) and cable surface temperature (T_{cs}) of the Calder Water circuit, along with its loading, are illustrated.

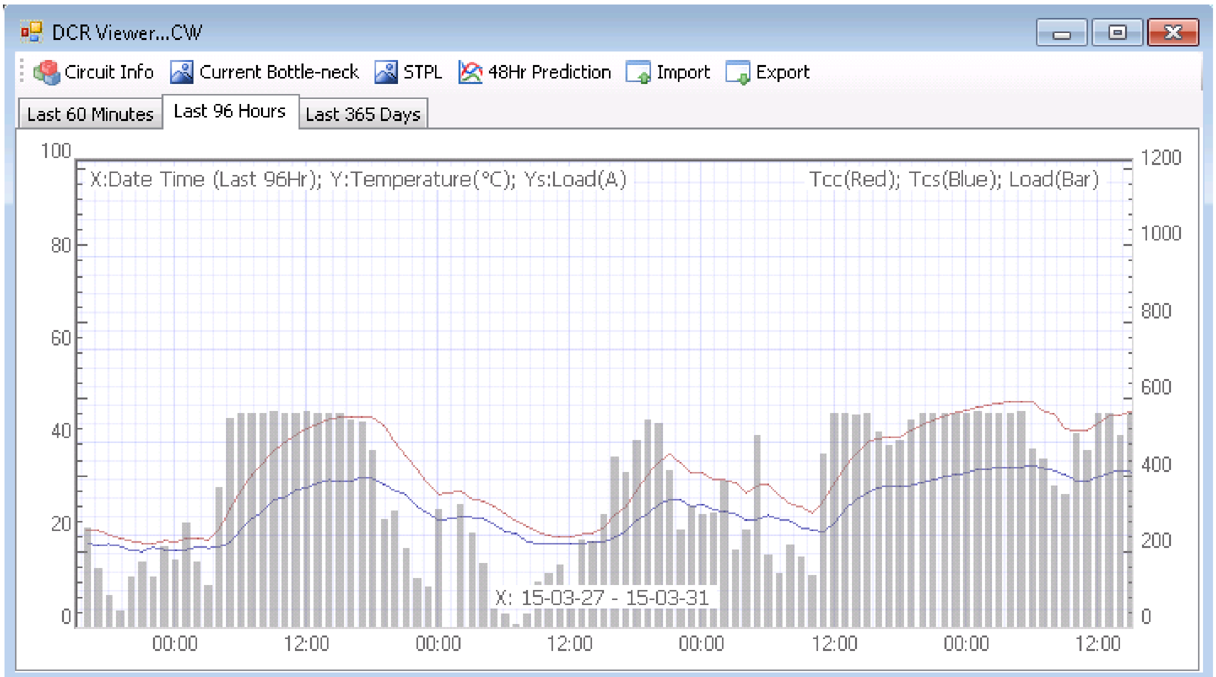

Figure 25: DCR feature reporting historic cable temperature – Calder Water example

Figure 26 is a snapshot of the DCR interface window, where the detailed radial temperature distribution from the optical fibre cable to the cable core is illustrated. The radial temperature distribution calculation is based on the thermal equivalent circuit model described in section 4.8.4. In this example, the optical fibre temperature is 29.4°C, the cable surface temperature is 29.6°C and the cable core temperature is 39.3°C.

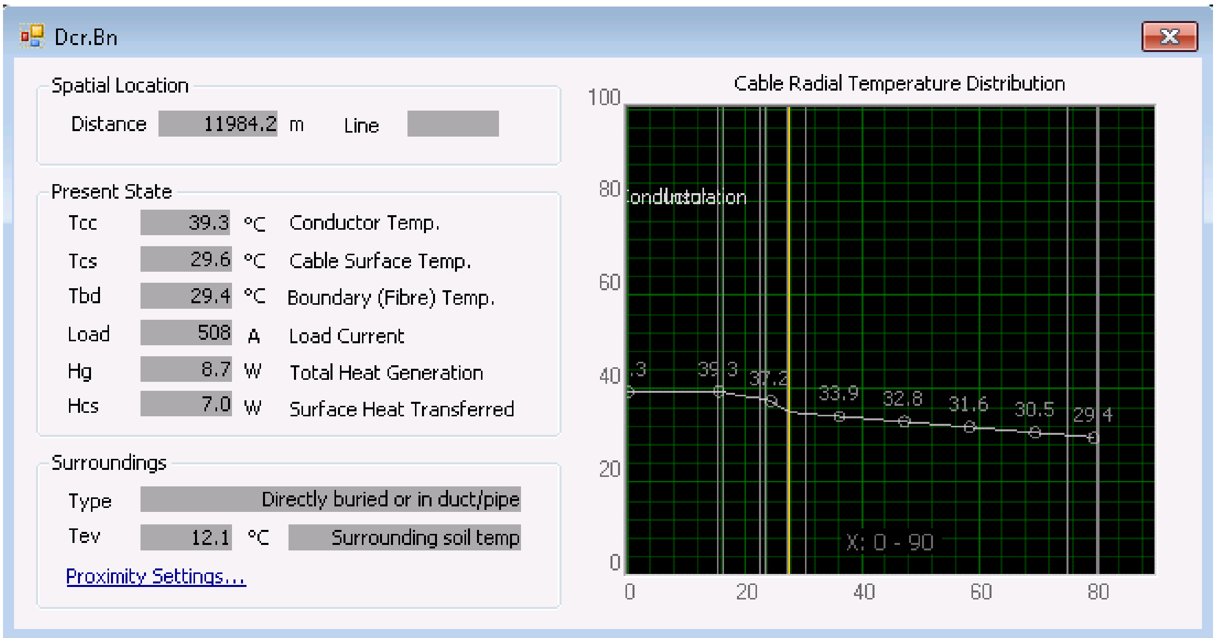

Figure 26: DCR feature for cable radial temperature distribution

One of the features of the DCR engine is the calculation of the Short-Term Permissible Loading (STPL) and Duration (STPD) based on the current cable core temperature. Figure 27 illustrates the DCR window which shows the maximum current that the cable can withstand for a given period of time. The short-term withstand capability of the cable is determined by two parameters: STPL and the STPD. STPL is calculated for a given maximum T_{cc} and a given duration, whereas STPD is calculated for a given maximum T_{cc} and a given loading.

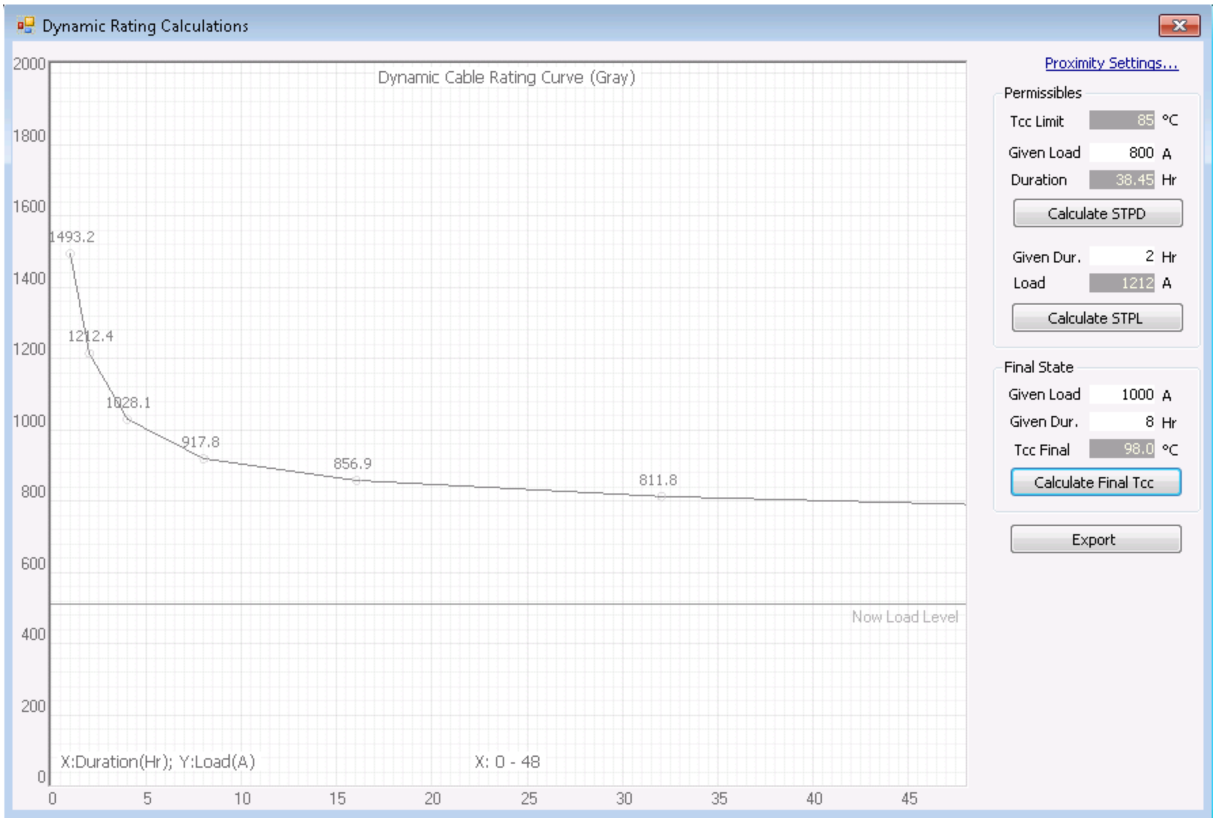

Figure 27: DCR dashboard feature for short-term withstand capability calculations

5.3 Continuous Cable Rating vs. Cyclic Cable Rating

As mentioned in section 4.4.1, the thermal rating or current carrying capacity of an underground cable is determined by three following elements:

1. Internal factors (cable construction, conductor design, insulation and sheath materials)
2. Factors dependant on installation and laying conditions
3. Operating conditions (e.g. continuous or cyclic loading)

Based on SPEN's equipment rating policy, in order to achieve the most economic XLPE cable designs, ratings are assigned which result in a maximum phase conductor temperature of 60°C at 11kV and 78°C at 33kV, as opposed to the manufacturer's maximum permissible temperature of 90°C. This enables the use of smaller cross section of copper screen wires than would otherwise be required to achieve the necessary earth fault capacity resulting in a more cost effective cable design

The load curve of the cable is also a crucial parameter for cable sizing. Based on the load curve, two different ratings may be calculated for a cable circuit:

1. Continuous rating
2. Cyclic rating

Continuous rating is the thermal capacity of the cable circuit whose load is assumed to be constant at all times. The cyclic cable thermal rating, however, is calculated based on the "typical" residential and commercial daily load variation. The load variations allow for heat dissipation from the cable and consequently a higher carrying capacity compared to continuous loading can be considered.

The cyclic rating usually determined in the UK industry is based on the "Load Curve G", as specified in part 3 of ER-P17. Load Curve G – see Figure 28 – is a typical domestic/commercial, 24-hour, load variation with a Loss Load Factor (LLF) of 0.5[1]. The LLF is a factor representing the losses, or gained heat, in a cable circuit. ER-P17 (Part 2, 1976) uses the following definition for LLF applied for cable rating calculations:

> *"it is assumed that power supplied in a given time (normally 60 minutes) are proportional to average current and power lost in the same time are proportional to the average value of current squared, in this guide the LLF is calculated for a 24-hour period; and are expressed in per unit values" "*

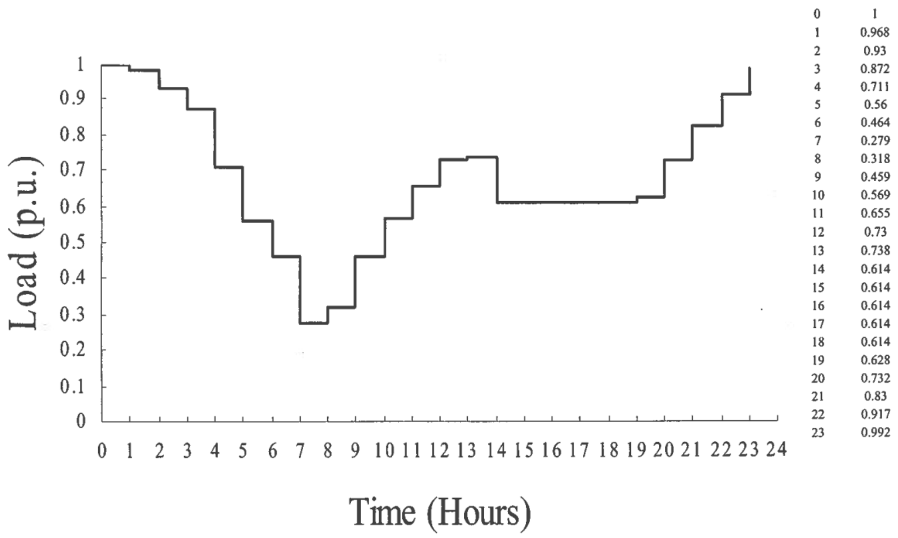

Figure 28: Load Curve G with an LLF of 0.5

According to SPEN's business as usual practices[2], the size of a cable considered for a windfarm connection is determined based on the continuous maximum output of the windfarm. The windfarm's output, however, varies stochastically with time and it may reach its rated output only for a short period of time. The variations in loading of the windfarm circuits allow for a higher heat dissipation level compared to the heat dissipation level assuming continuous circuit loading. In the following section, the historical loading of the windfarms are analysed and the associated LLFs are calculated.

5.4 Loadings of the WindFarm Cable Circuits

In this section the historical loadings of the Calder Water and Whitelee cable circuits from 01/01/2014 to 12/03/2015 are presented. This data is used to calculate the LLFs as indications of the cable circuit utilisation. For consistency with ER-P17, daily LLFs (24h period) were calculated, where the maximum possible loading of each circuit is taken to be the absolute maximum recorded output of the whole 15-month period.

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[1] $\frac{1^2+0.968^2+0.93^2+\cdots}{24} = 0.5$

[2] SP Energy Networks ESDD-02-007 (issue 6) "Equipment Ratings"

Due to communication issues between the RTU and the transducer, which were only resolved later in the project, the historic loadings of West Browncastle are not available to be presented in this report. It should be also noted that the Dungavel windfarm circuit loading is not available as this circuit is scheduled to be energised in the third quarter of 2015.

5.4.1 Calder Water windfarm

Figure 29 shows the loading of the Calder Water 33kV cable circuit. The maximum loading of this circuit reaches 625A on 31/01/2014. It should be noted that i)there was a period between 13/05/2014 and 04/07/2014 when circuit loading data was unavailable, ii)there is also a prolonged period in September 2014 during which the Calder Water windfarm reduces to nearly zero output.

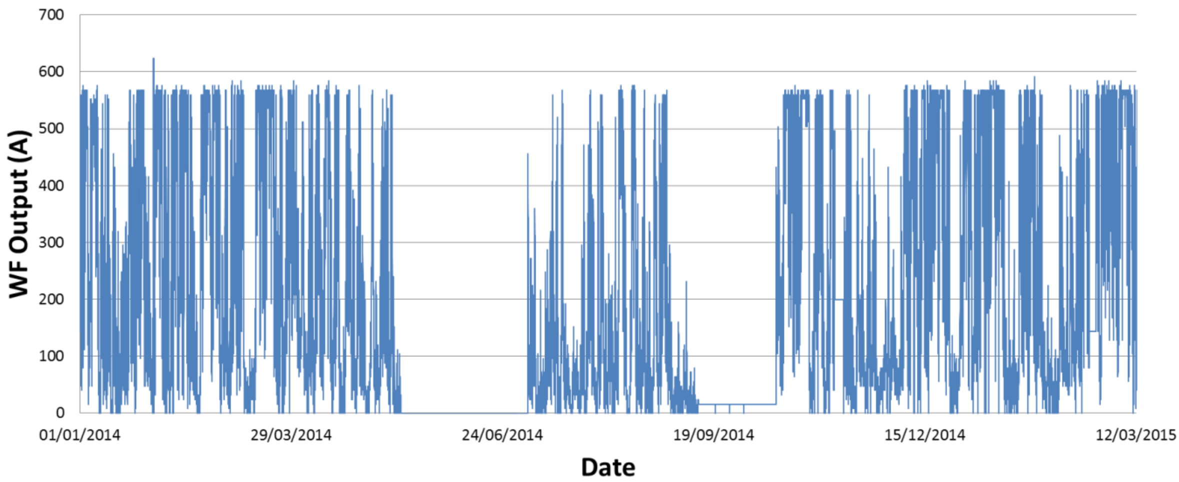

Figure 29: Calder Water circuit loading

Figure 30 shows the variation of the daily LLFs of the Calder Water circuit.

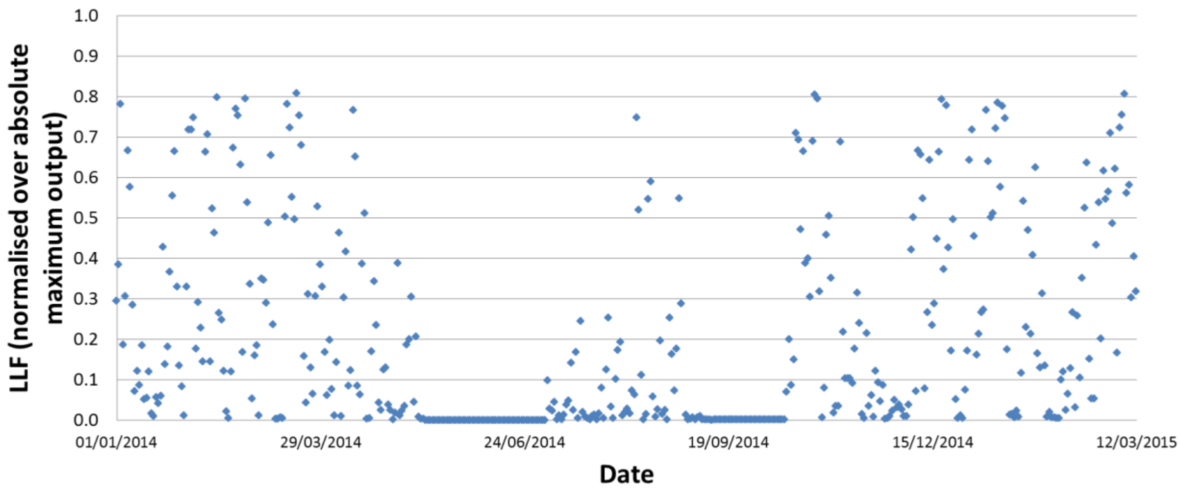

Figure 30: Calder Water circuit daily LLF variation

The variation of the LLF is quite erratic and no particular pattern can be observed. The LLF does not greatly exceed 0.8 at any time.

Figure 31 shows the cumulative frequency of Calder Water daily LLFs. It can be seen that for 80% of the time, the Calder Water LLF was less than 0.5. There is only a 20% probability for LLFs greater than 0.5.

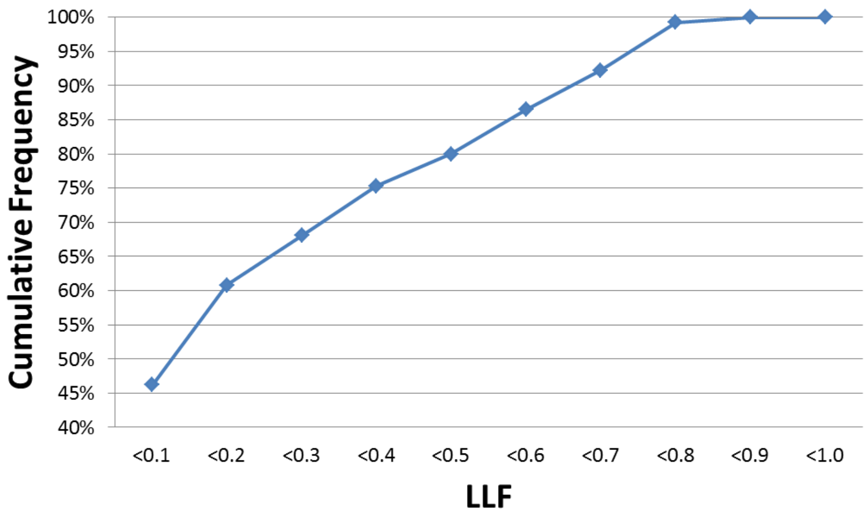

Figure 31: Calder Water cumulative frequency of the daily LLFs

5.4.2 Whitelee windfarm

Figure 32 shows the loading of the Whitelee 275kV cable circuit from 01/01/2014 to 15/03/2015. The maximum loading of this circuit was 660A and was observed on 19/03/2014 and again on 20/03/2014.

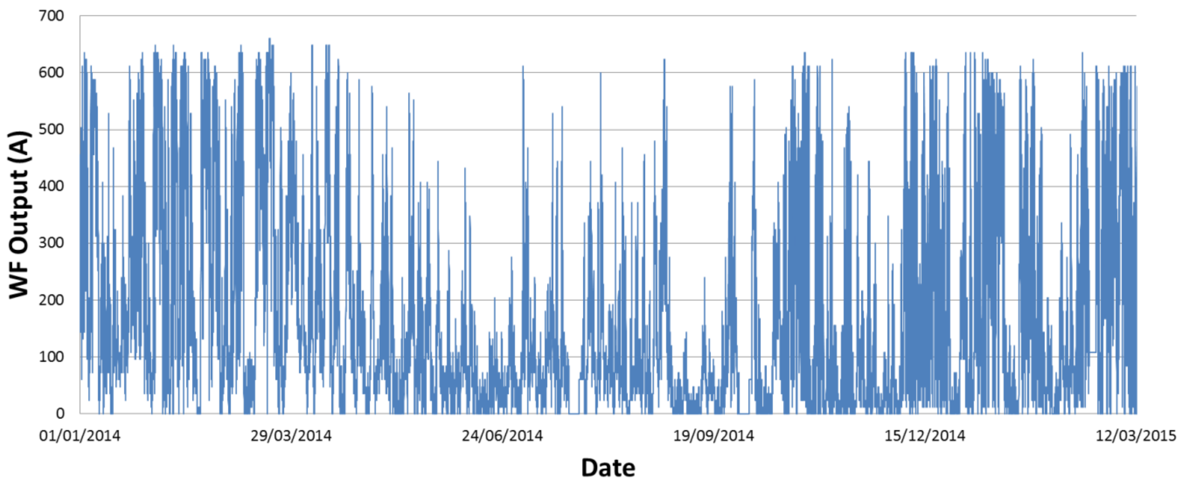

Figure 32: Whitelee circuit loading

Figure 33 below shows the variation of the daily LLF.

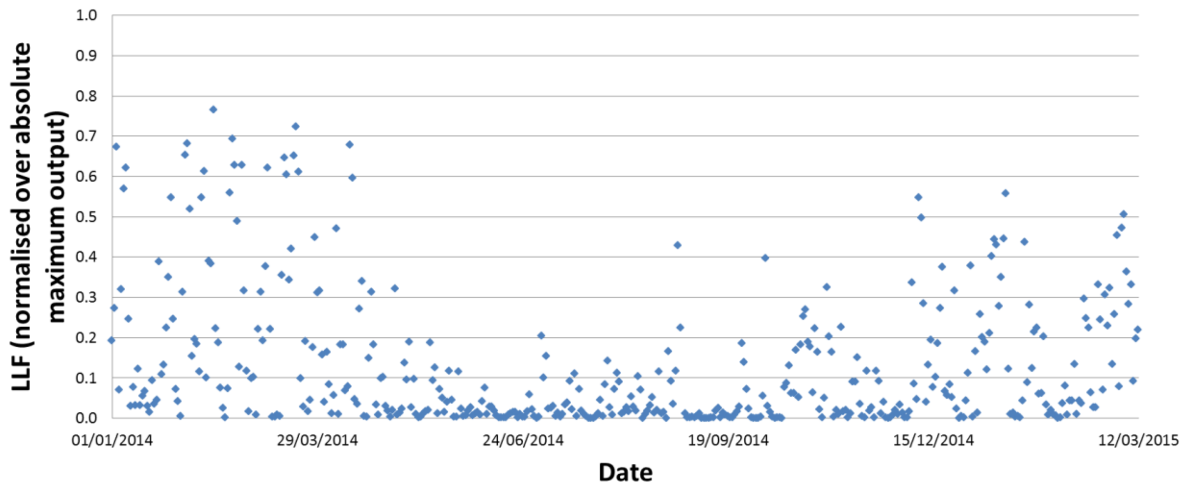

Figure 33: Whitelee circuit daily LLF variation

Any instances that the equipment failed to measure the loadings were discounted from the calculation of the LLFs. There are again two periods, one around June 2014 and the other one around September 2014, during which the windfarm appears to have had consistently low output.

The variation of the LLFs is again erratic, but a reasonable increase in loading during wintertime can be observed.

Figure 34 shows the cumulative frequency of these daily LLFs. Around 94% of the time the LLF is at or below 0.5.

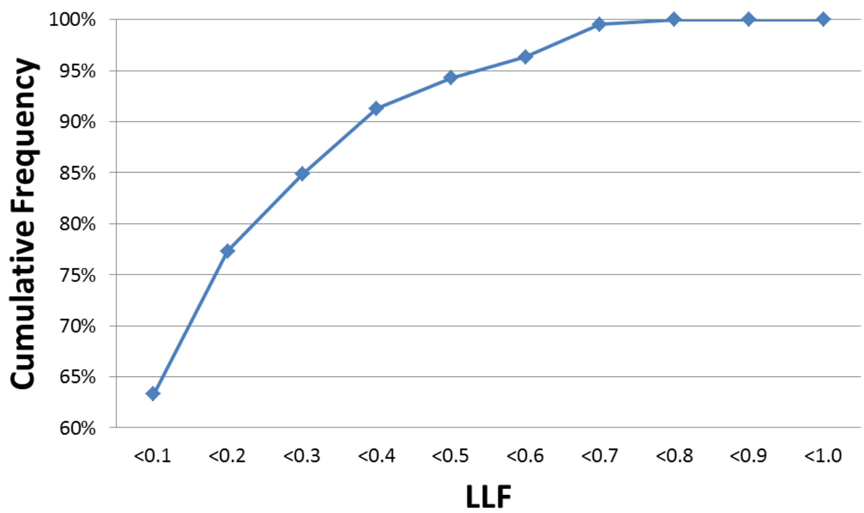

Figure 34: Whitelee cumulative frequency of the daily LLFs

The daily LLF variations of the Calder Water and Whitelee windfarms showed that the actual heat dissipation levels in these cable circuits is likely to be higher than the heat dissipation levels assumed for a continuous cable loading. In other words, considering dynamic ratings, rather than continuous rating, seems more relevant for sizing the windfarm cable circuits. SPEN plans to use the learning from this project and explore further the application of cable dynamic rating for windfarm circuits through a new project funded through the Network Innovation Allowance (NIA) mechanism.

5.5 Cable Temperature Profiles

The DTS system, which was implemented in this project, recorded the optical fibre temperature for every half an hour for each of the monitored circuits. By taking these half-hour measurements, hourly minimum, maximum and average measurements were automatically generated by the DTS.

The optical fibre temperatures are used together with detailed thermal models of the different layers of the cables to calculate the cable core temperatures. There is a strong correlation between the optical fibre temperatures and the core temperatures as they follow similar patterns.

5.5.1 Calder Water windfarm

5.5.1.1 High LLF vs. Low LLF

The hourly maximum measurements of the Calder Water optical fibre shown in Figure 35 and Figure 36 are for two days representing a high LLF and a low LLF conditions respectively.

Figure 35 shows the temperature profile of the whole optical fibre length on 07/03/2015 at 12:00, which was identified as a day with a high LLF (0.806). Since the Calder Water optical fibre is double-ended there are two measurements for each point of the cable length. The part of the graph up to the black “End” line, representing the end of the cable route, is the forward measurements. Beyond that “End” line, the data are the reverse measurements, where the optical fibre is looped back towards East Kilbride South substation. It can be noted that the measurements are well-mirrored around the “End” line.

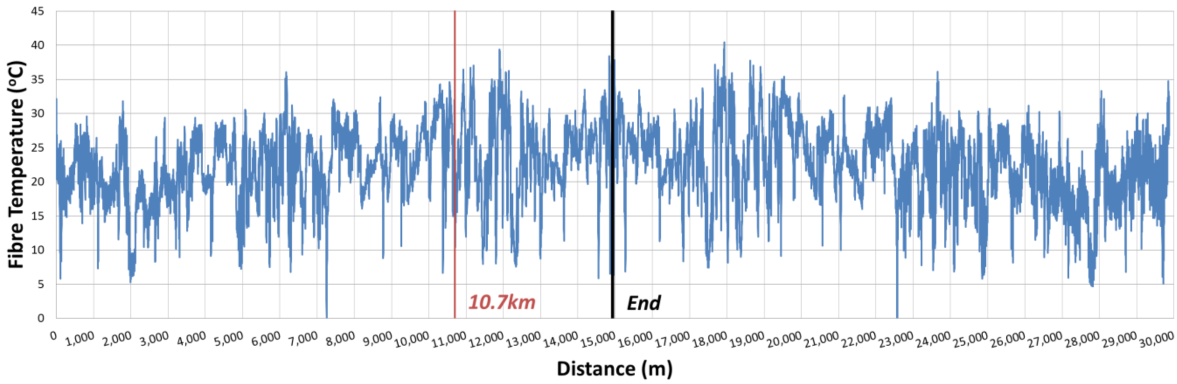

Figure 35: Calder Water optical fibre temperature profile on 07/03/2015, 12pm (high LLF)

The length of the shared trench (10.7km) is also marked. The optical fibre temperatures up to that point are not higher than those between the 10.7km and the end of the optical fibre. However, it should be noted thatnot all 33kV cable circuits were energised and it was not expected to see a significant temperature increase along the shared trench length. The maximum optical fibre temperature during this day reached around 40.0°C.

Figure 36 shows the temperature profile at 12:00 on a low, non-zero LLF day, which was the 01/02/2015 (LLF = 0.135). Compared with Figure 35, the measured temperature of the optical fibre is significantly lower as expected due to the low LLF. The maximum optical fibre temperature for this day was around 20.0 °C.

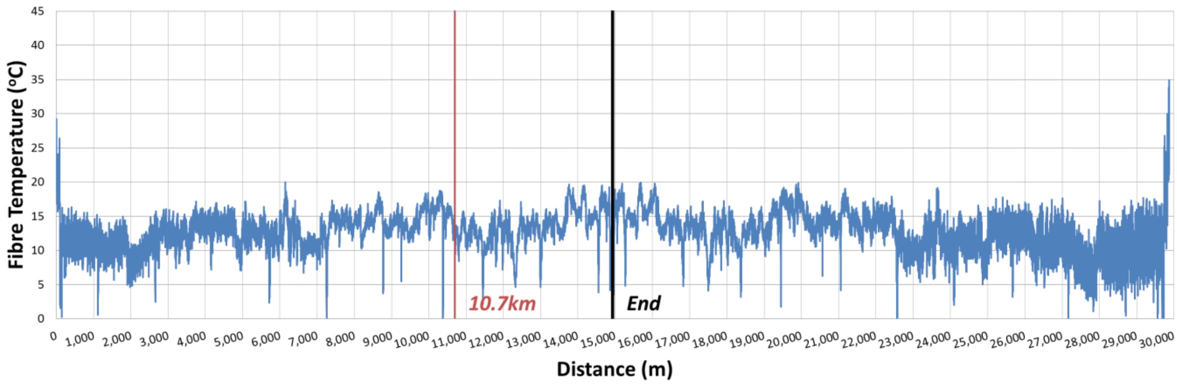

Figure 36: Calder Water optical fibre temperature profile on 01/02/2015, 12pm (low LLF)

5.5.1.2 Maximum optical fibre temperatures & critical points

Figure 37 shows the maximum optical fibre temperature of the entire circuit for every half an hour of the studied period against the loading of the circuit.

The results show that there is strong correlation between the circuit loading and the optical fibre temperature. Nevertheless, the temperature variations lag the circuit loading variations. This is due to heat inertia of the cable. In other words, once there is sudden change in circuit loading, the cable temperature follows a gradual change rather than a sudden variation. Between 02/02/2015 and 13/02/2015 no optical fibre temperatures were captured due to a communication interruption that occurred in the DTS workstation.

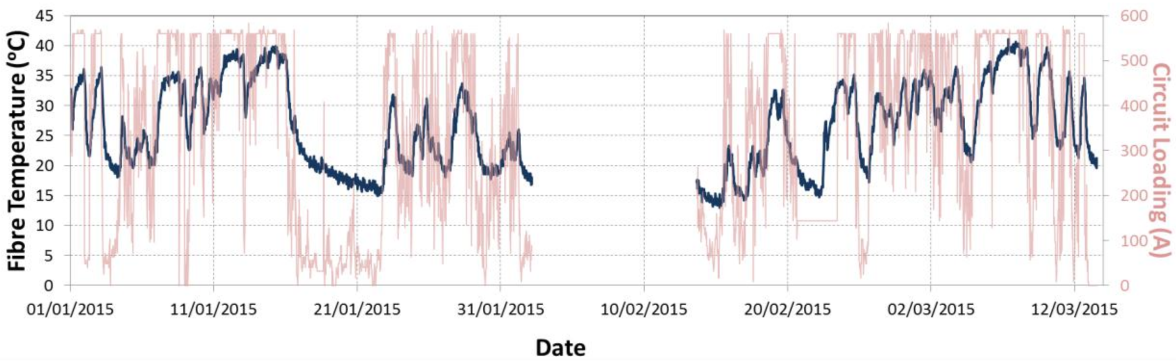

Figure 37: Calder Water maximum optical fibre temperatures and circuit loading

Figure 38 shows the location of the daily maximum optical fibre temperatures along the circuit length. Four zones of interest can be observed: one around 6km, one around 10km, one around 12km and the last one around 14km, which is the end of the optical fibre route at the windfarm's substation and where the optical fibre is looped back towards East Kilbride South substation. The 10km and the 12km, appear to be locations around optical fibre cable joints, where cables are unducted and consequently the optical fibre is in contact with the cables . The 6km zone is the crossing point of the Whitelee 275kV cable and the 33kV cable circuits. At this point, the 33kV cables burial depth was increased in order to pass under the Whitelee 275kV cable.

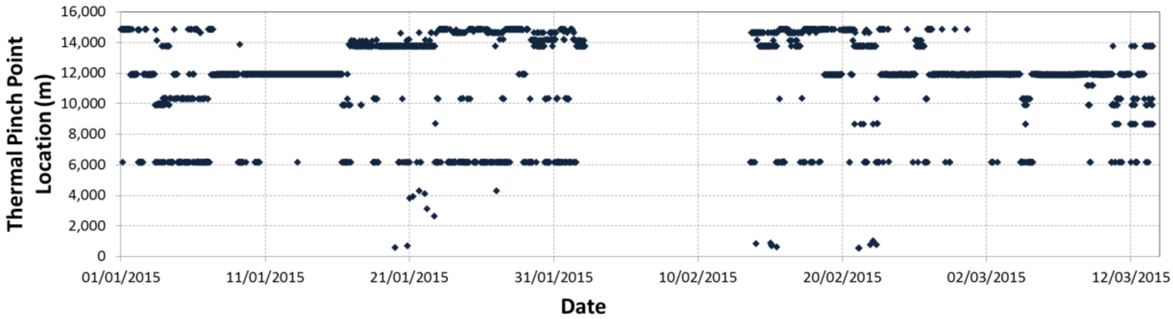

Figure 38: Critical points along the Calder Water circuit

5.5.2 West Browncastle windfarm

5.5.2.1 High LLF vs. Low LLF

Figure 39 and Figure 40 show the optical fibre temperatures of the West Browncastle windfarm cable circuit on 07/03/2015 and 01/02/2015 respectively, at 12:00pm.

The temperatures on 07/03/2015 are higher than those on 01/02/2015, which would again agree with the high and low LLFs for these dates. The temperature profiles of West Browncastle on these two dates are similar to those of Calder Water – see Figure 36 and Figure 35. It is an expected result as the two cable circuits are in the same trench for most of their route and they are exposed to similar environmental conditions.

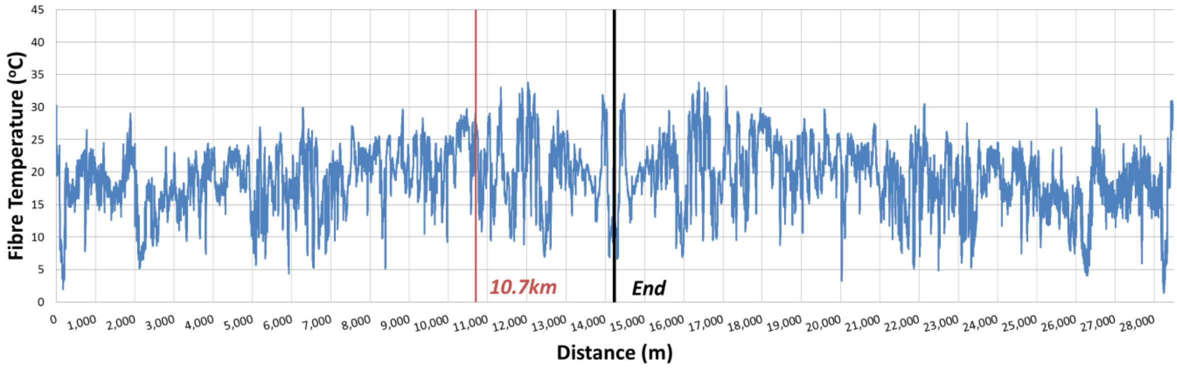

Figure 39: West Browncastle optical fibre temperature profile on 07/03/2015, 12pm (assumed high LLF)

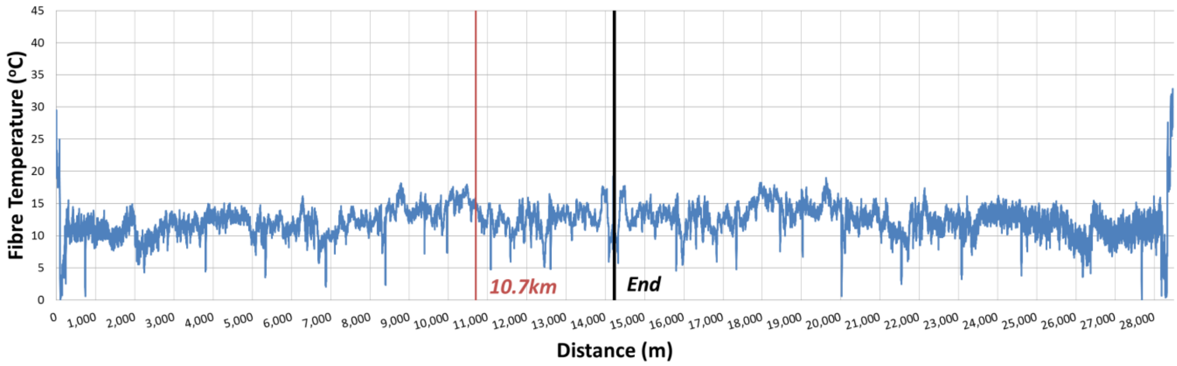

Figure 40: West Browncastle optical fibre temperature profile on 01/02/2015, 12pm (assumed low LLF)

5.5.2.2 Maximum optical fibre temperatures & critical points

Figure 41 shows the maximum optical fibre temperatures along the West Browncastle circuit. The West Browncastle temperature variation follows closely the pattern of the Calder Water variation (shown in Figure 37), however, the average temperatures is around 6°C lower than Calder Water.

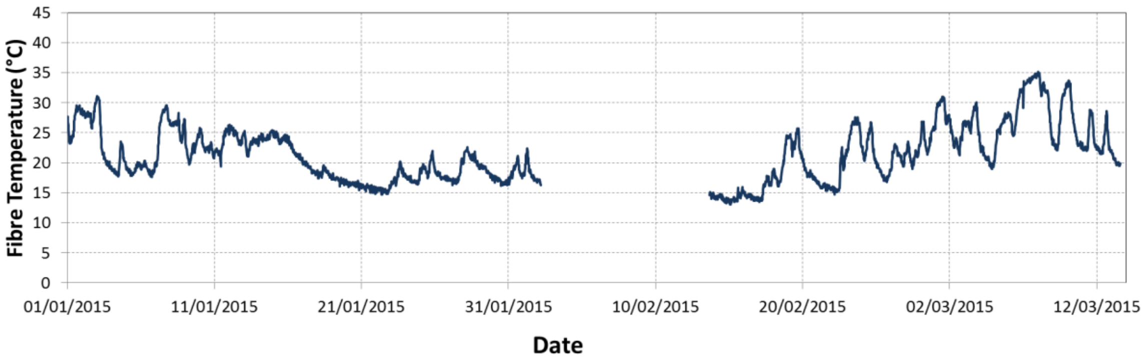

Figure 41: West Browncastle maximum optical fibre temperatures

The critical thermal points along the circuit (Figure 42) can be categorised in three zones: one around 8.5km, one around 10km and one around 12km. With the exception of the 8.5km, the other pinch points are similar to the Calder Water critical zones. 8.5km zone appear to be locations around optical fibre cable joints, where cables are unducted and consequently the optical fibre is in contact with the cables.

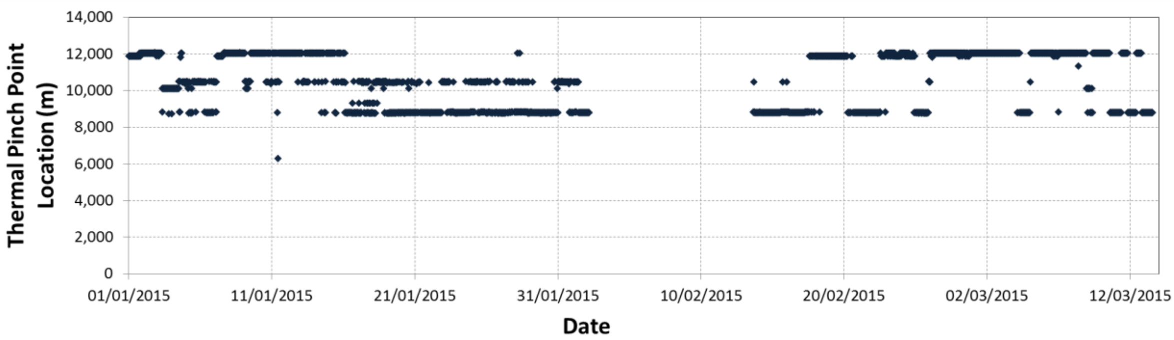

Figure 42: Critical points along the West Browncastle circuit

5.5.3 Dungavel windfarm

The Dungavel windfarm was not energised within the lifetime of this project. Nonetheless, the optical fibre was installed for the Dungavel cable along the length of the shared trench and so it allows for the monitoring of the temperature variations purely due to external factors and not due to circuit loadings. The external factors were a combination of the thermal effects from the Calder Water and West Browncastle circuits, soil temperature variations and depth of burial.

5.5.3.1 High LLF vs. Low LLF

For consistency, the two dates that were examined for Calder Water and West Browncastle, 01/02/2015 and 07/03/2015, were used for demonstrating the Dungavel temperature profile as well – see Figure 43 and Figure 44. The temperature profile of Dungavel during these two days is following the same trend as Calder Water and West Browncastle.

It is evident and reasonable that the optical fibre temperatures were significantly lower than those of Calder Water and West Browncastle as the Dungavel circuit did not carry any current.

The differences between a high LLF and a low LLF are not as noticeable, because of the fact that they can only be attributed to the respective differences between the two days of the Calder Water and West Browncastle circuits and not to the un-energised Dungavel circuit.

As in the cases of Calder Water and West Browncastle, the recorded temperatures are much higher at the first few metres that lie within East Kilbride South substation.

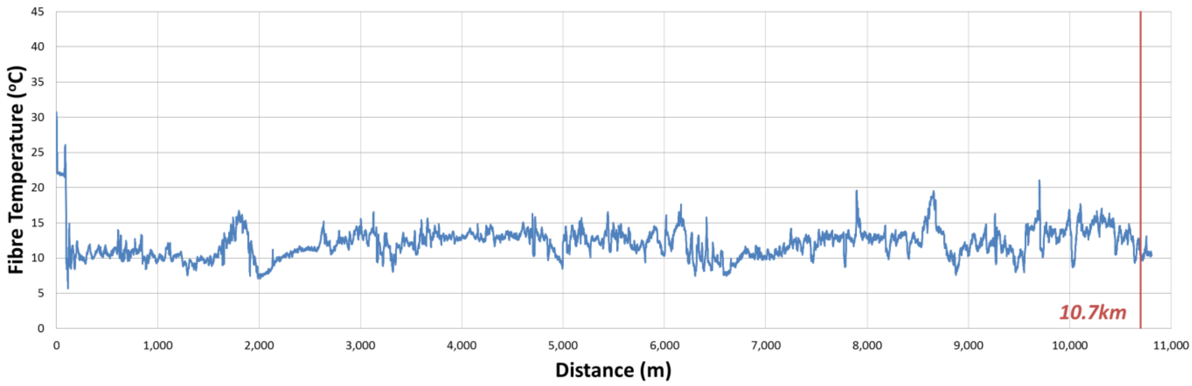

Figure 43: Dungavel optical fibre temperature profile on 07/03/2015, 12pm (assumed high LLF)

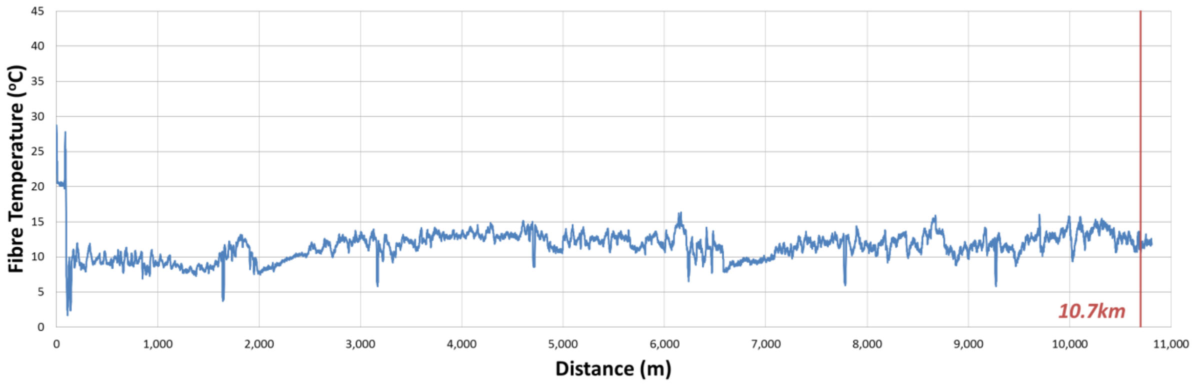

Figure 44: Dungavel optical fibre temperature profile on 01/02/2015, 12pm (assumed low LLF)

Currently, the DTS monitoring of the Dungavel optical fibre cable extends up to the end of the shared trench. Temperature monitoring of the remaining part of the Dungavel cable route (another 10.7km approximately) is scheduled to be included in the DTS measurements in the third quarter of 2015, after completion of the Dungavel cable installation.

5.5.3.2 Maximum optical fibre temperatures & critical points

The optical fibre temperatures (Figure 45) follow a relatively similar pattern with those of Calder Water and West Browncastle, experiencing an increase around 15/01/2015 to17/01/2015, followed by a drop and then another increase towards the end of the period. These temperature variations clearly demonstrate temperature rise due to being in thermal zones of other cable circuits. In this case, the temperature rise due to mutual thermal impact is around 8°C on Dungavel. This confirms that for calculating the thermal rating of a cable circuit the close proximity to other cable circuits and their thermal impacts should be taken into account.

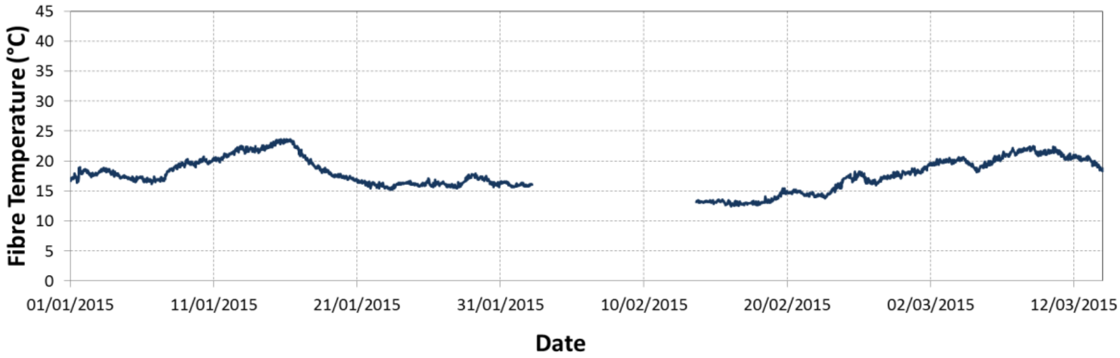

Figure 45: Dungavel maximum optical fibre temperatures

The critical zones (Figure 46) are a mix of the Calder Water zones and those of West Browncastle, one at 6km, one at 8km and one at 10km. This demonstrates that the un-energised Dungavel circuit is affected by the other two circuits in the trench.

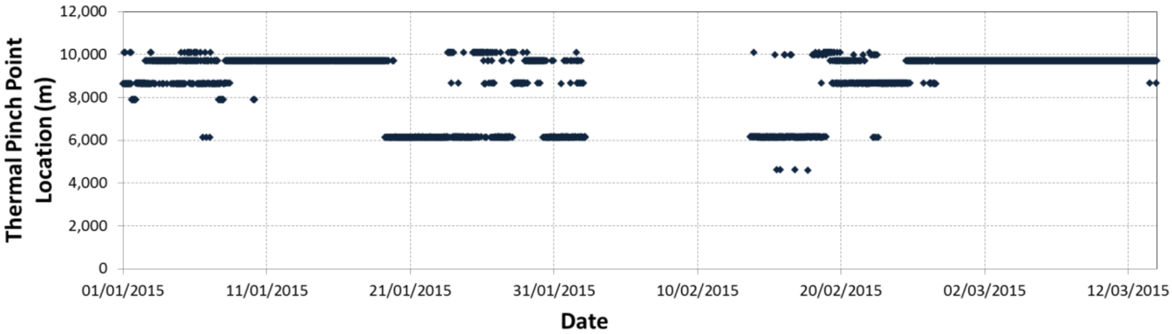

Figure 46: Critical points along the Dungavel circuit

5.6 Causes of variations in temperature profile

In this section, the optical fibre temperature profile along the cable is used to examine the possible causes of the temperature variations. The causes of the temperature variation can be a change in the surface terrain, a change in the burial depth or proximity to other cables. For the purposes of this analysis, the notable temperature variations were identified on Calder Water circuit and the causes of the temperature change were examined based on geographical and cable installation information. Figure 47 shows the temperature profile along the Calder Water circuit in which some of the sudden temperature changes are identified and numbered.

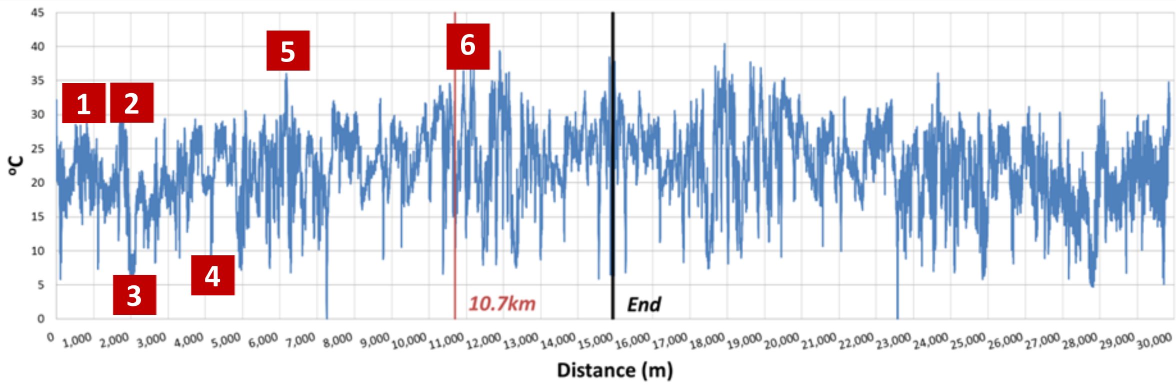

Figure 47: Calder Water thermal pinch point identification

Location 1, Zone 2 (see Figure 48): The temperature rise at this location occurs around a crossing point of one of the Whitelee 275kV circuit and the 33kV cable circuits. Around this crossing point, the burial depth of 33kV circuits was increased to allow room for passing under the existing 275kV cable. The increased depth around this location and being in zone of thermal effect of 275kV cable are the reasons for the temperature rise around this location.

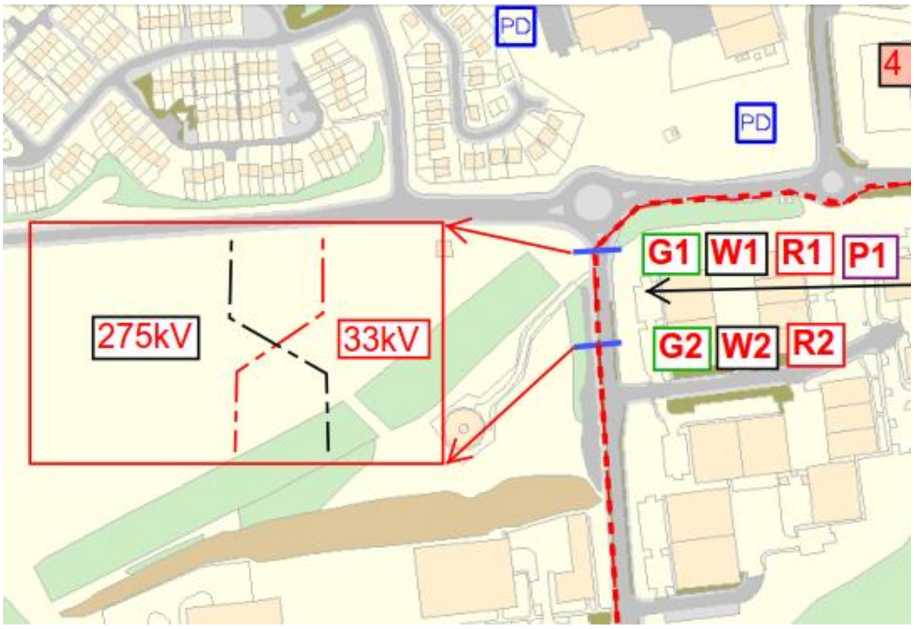

Figure 48: Location 1 – temperature rises due to an increase in depth and crossing of an existing 275kV cable

Location 2, Zone 6 (see Figure 49): The distance between cable circuits at this location decreases due to the pyramid configuration used for 33kV cables installations. Due to the change in separation, the mutual thermal effects between the cable circuits are higher around this location, which consequently causes the cable temperature rise.

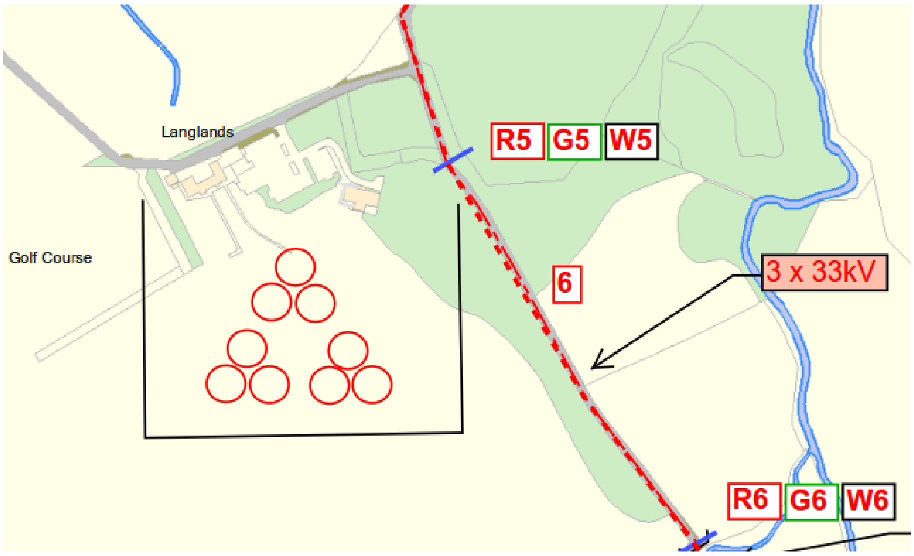

Figure 49: Location 2 – temperature rises due to the change in the configuration of the 33kV cables

Location 3, Zone 7 (see Figure 50): The cable route around this location runs though the riverbed. The temperature drop at this location is due to better heat dissipation with the ground surface and also cable circuits are likely to be submerged around this location.

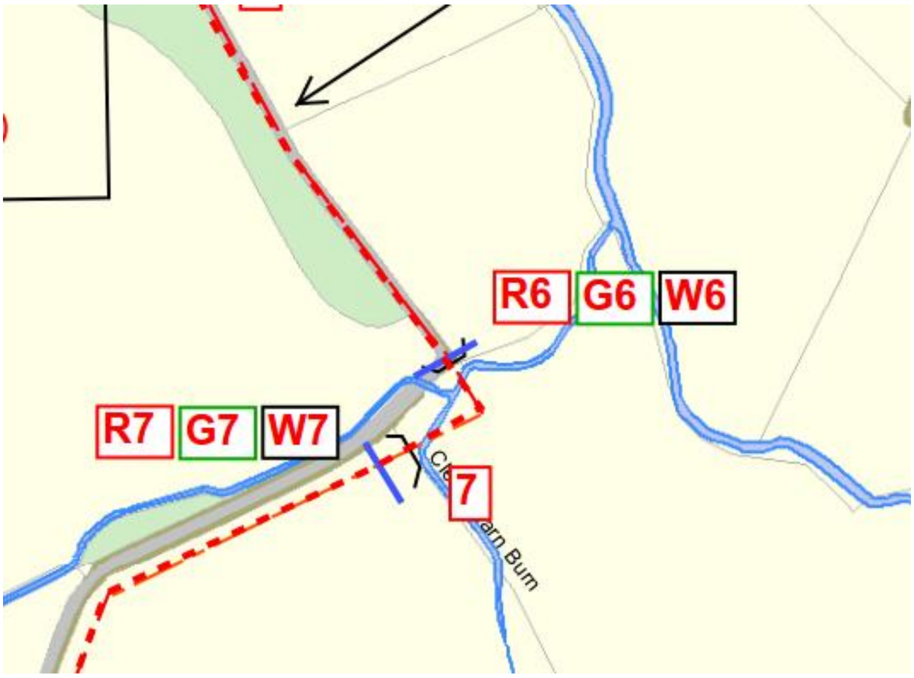

Figure 50: Location 3 – temperature drops due to proximity to the river

Location 4, Zone 17 There is a chamber at this location and temperature drop occurs as the optical fibre has been moved away from the power cable.

Location 5, Zone 25 (see Figure 51): This location is another crossing point between the Whitelee 275kV cable circuits and the 33kV cable circuits. The depth of the 33kV cables is increased around this location to allow room for passing under the existing 275kV cable. The increased depth around this location and being in the zone of thermal effect of the 275kV cable circuits are the reasons for the temperature rise.

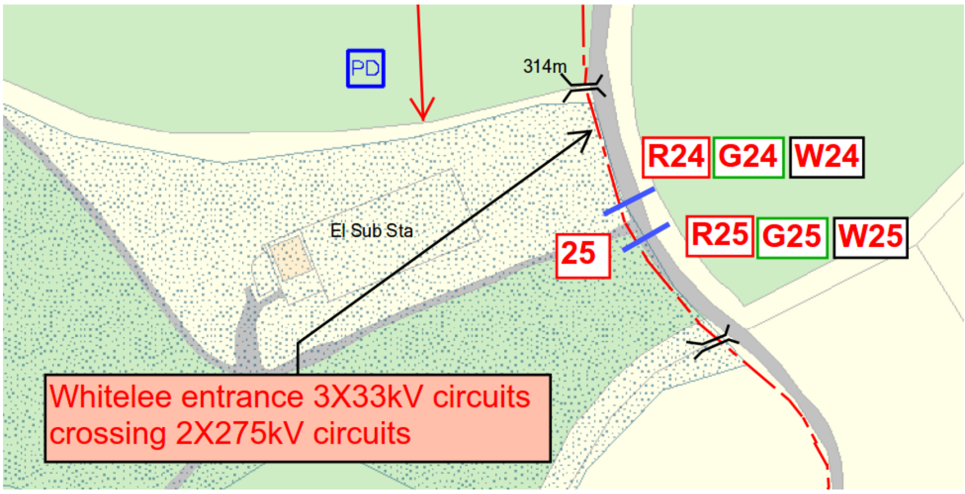

Figure 51: Location 5 – temperature rises due to an increase in depth and crossing of two existing 275kV cables

Location 6, Zone 32 (see Figure 52): There is a river crossing around this location. The cable route runs under the riverbed, but before and after the river the depth of burial has been significantly increased to allow passing under the riverbed. As a result of this change in depth, the temperature rises; however, there is a notable temperature drop around the location where the cable is under the river and possibly submerged.

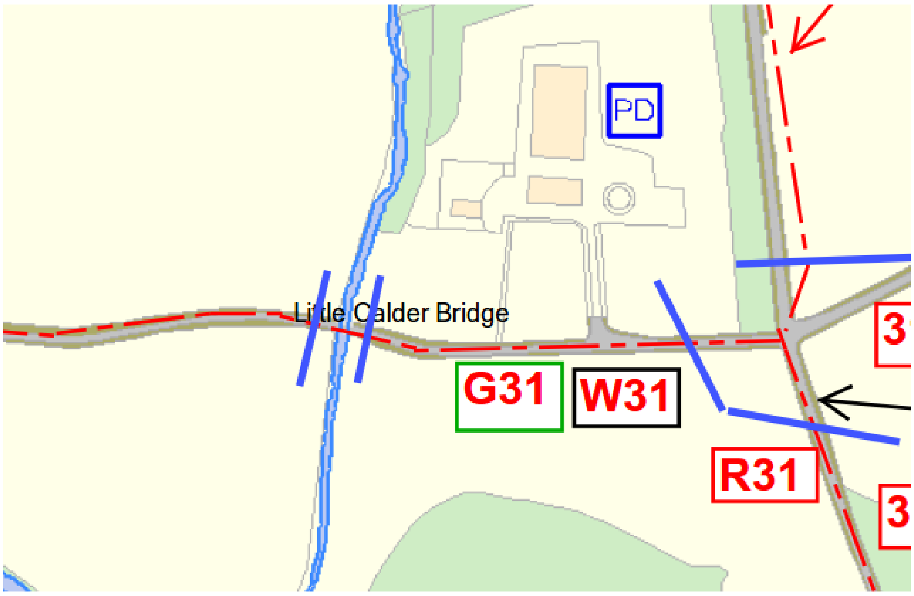

Figure 52: Location 6 – there is a river crossing and the depth of burial increases before and after the river

5.7 DTS Validation

The temperature monitored by the DTS system is validated by using an independent temperature sensor (Tinytag). Two locations representing indoor and outdoor conditions were selected for validation purposes:

i) East Kilbride South substation: a Tinytag was placed in the control room, outside the DTS cabinet, next to the optical fibre calibration cables, which are coiled up and hooked on the wall.
ii) Chamber 17: Tinytag was placed in Chamber 17 next to the Calder Water optical fibre.

The temperature data recorded by the Tinytags and the DTS system at the two aforementioned locations were compared for a 10-day period, between 18/02/2015 and 28/02/2015. The results of this comparison show that the reported temperatures by the Tinytag and the DTS system follow closely the same variations (Figure 53 and Figure 54). The sudden changes in the DTS data are not valid and SPEN is planning to investigate what causes them as part of a follow-on NIA project. The average absolute differences between the two temperatures recorded by Tinytag and DTS system are 1.30°C and 0.65°C at East Kilbride South substation and Chamber 17 respectively. The differences are within the acceptable limits based on the DTS system and the Tinytag accuracies.

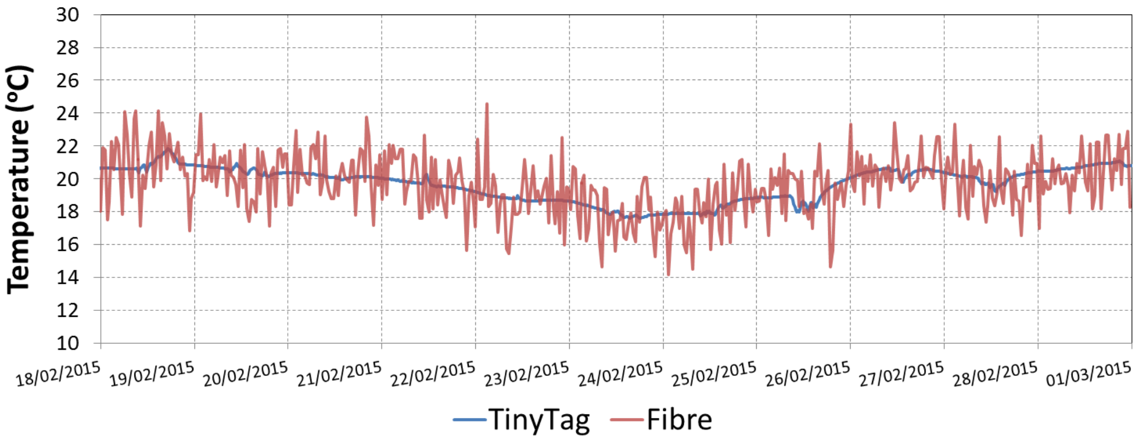

Figure 53: Comparison between temperatures recorded by Tinytag and the DTS system at East Kilbride South substation

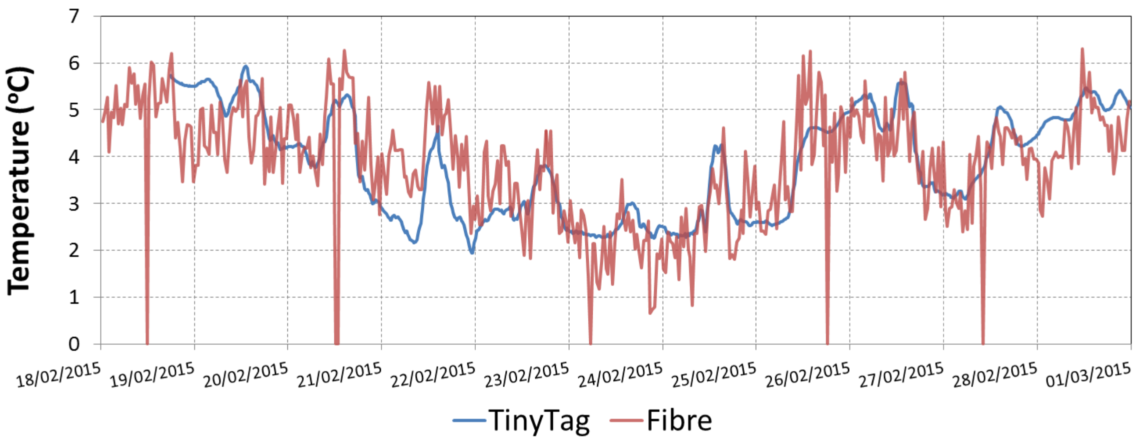

Figure 54 : The comparison between temperatures recorded by Tinytag and the DTS system at Chamber 17

6 Performance Compared to Original Project Aims, Objectives and Success Criteria

The project successfully delivered its intended aims and objectives. The following key outcomes of the project are in line with the aims and objectives initially described in the project registration pro-forma:

- The Dynamic Cable Ratings (DCR) of all the 33kV cables, except Dungavel, are determined and the DCR values of cable circuits are available through the DCR and DC-View dashboards, which have been specifically designed and customised for this project. The real-time outputs of the windfarms are also transmitted from SPEN's PowerNet network to the DCR workstation. Dungavel circuit is scheduled to be energised in third quarter of 2015, once this circuit energised the DCR values will be also available for this circuit.
- The comparison between maximum recorded fibre temperatures representing the surrounding temperature of the cable with the maximum permissible operating for cable core temperature (78°C for 33kV XLPE) suggests that there may be additional network capacity available, which could be utilised if the windfarm developers decide to increase their outputs. This is subject to further assessment for at least a 12-month period after Dungevel windfarm is commissioned in third quarter of 2015.

The following key points demonstrate that the project has met its success criteria:

- The real-time full length (with 1 metre granularity) temperature profiles of the 33kV Calder Water, West Browncastle, and 10.7km (out of 21.4km) of Dungavel windfarm circuits are now available through a user-friendly dashboard.The temperature profile of the remaining 10.7km Dungavel circuit will be available after this windfarm circuit is energised in third quarter of 2015. The delay in energisation of this circuit was only due to the customer decision and change in the ownership of the windfarm.
- The measured temperature values are then used by DCR algorithms to determine the maximum core temperature and location it occurs. DCR algorithms use an equivalent thermal circuit simulating the thermal conditions of the cable along with the real-time optical fibre temperatures.

  The results of the DCR calculations of Calder Water and West Browncastle cable circuits are recorded in the SPEN's data historian for every 30 minutes. The DCR calculations will be also available for Dungavel circuit when this circuit is commissioned in third quarter of 2015. These data may be used to estimate the available headroom for any period required.

The project has largely succeeded in delivery of its original aims and objects In this section the performance of the project is evaluated against the initial aims, objectives and success criteria which were initially described in Project Registration Pro-forma.

6.1 Project Performance Relative to its Aims and Objectives

The performance of the project is compared against original aims and objectives as follows:

Determine dynamic cable ratings for three cable circuits (3 x 33kV) and assess the impact the renewable generation from the three windfarms will have on these circuits

The Dynamic Cable Ratings (DCR) of all the 33kV cables, except Dungavel, are determined and the DCR values of cable circuits are available through the DCR and DC-View dashboards, which have been specifically designed and customised for this project. The DCR workstation hosts the DCR calculation engine, which is a Bandweaver Ltd product. The DCR calculation engine uses real-time optical fibre temperature measurements together with a detailed thermal model of the cable circuit to determine the Short-Term Permissible Loading (STPL) of the cable circuits for a given loading duration. As a default setting, the permissible loadings of cable circuits for the next 48-hour period are given in the DCR dashboard. Nonetheless, users can determine the STPL for any other given duration. The real-time outputs of the windfarms are also transmitted from SPEN's PowerNet network to the DCR workstation where the DCRs can be assessed against variations in the windfarms' outputs on a real-time basis. All the calculated DCR values and measured data are also recorded in separate files and also SPEN's data historian for the purpose of off-line assessments. Dungavel circuit is scheduled to be energised in third quarter of 2015, once this circuit energised the DCR values will be also available for this circuit.

Inform future cable rating calculations for other projects, which could negate or postpone the requirement for upgrading/reinforcing the distribution system

The Distributed Temperature Sensing (DTS) system implemented in this project provides complete visibility of the temperature profile along the cable circuits under different loading conditions. The initial data analysis of the historical optical fibre temperature data showed that the temperature around the cable reached 40°C for a high wind condition (maximum windfarm output). Comparing this maximum recorded fibre temperature with the maximum permissible operating temperature (78°C for 33kV XLPE cables), it is suggested that there may be additional network capacity available, which could be utilised if the windfarm developers decide to increase their outputs and potentially network reinforcement could be deferred or cancelled. The output power of the windfarms follows a stochastic variation that may allow cable circuits to dissipate heat during high wind periods. This suggests that a dynamic cable rating rather than a continuous thermal rating could be considered for future windfarm connections. In the continuation of this work under a new NIA registered project (NIA_SPEN0003), further analysis will be conducted on temperature and loading of the cable circuits for at least 12 months period to develop recommendations for future windfarm cable circuit sizing calculations.

6.2 Project Performance Relative to its Success Criteria

The performance of the project is compared against three success criteria initially defined in Registration Pro-forma as follows:

The temperature can be monitored across all three cables along the full cable route being monitored

The real-time full temperature profiles of the 33kV Calder Water, West Browncastle, and 10.7km (out of 21.4km) of Dungavel windfarm circuits are now available through a user-friendly dashboard. The temperature profile of the remaining 10.7km Dungavel circuit will be available after this windfarm circuit is energised in third quarter of 2015. The delay in energisation of this circuit was only due to change in the ownership of the windfarm. The micro-ducts were installed along all three 33kV cable circuits under consideration from East Kilbride South substation. 12-core optical fibres were blown into the micro-ducts and connected to the DTS equipment located at East Kilbride South substation. The temperature of the optical fibre, representing the cable's surrounding temperature, for every 1m is measured. The measured temperature values are then used by DCR algorithms to determine the maximum core temperature and location it occurs.

Dynamic cable ratings are determined with associated wind generation output

The DCR of each 33kV circuit is calculated by the DCR algorithms hosted in the DCR workstation. DCR algorithms use an equivalent thermal circuit simulating the thermal conditions of the cable along with the real-time optical fibre temperatures in order to calculate the DCRs. The results of the calculated dynamic thermal ratings and the associated real-time windfarm outputs are visualised through the DC-View dashboard.

Available head room capacity can be determined for the three windfarm cable circuits

The results of the DCR calculations for any of the three cable circuits are recorded in the SPEN's data historian every 30 minutes. This data could be used to estimate the available headroom for any period required. In addition, DCR results are available through DC-View on a real-time basis, which can be used for dynamic headroom calculations. SPEN plan to carry out a thorough data analysis on a 12 month period data, after the energisation of the Dungavel windfarm, to determine the available headroom at different loading conditions for all windfarm circuits.

7 Required Modifications to the Planned Approach During the Course of the Project

The following modifications were made to the original planned approach:

- Installation of DTS equipment at East Kilbride South substation rather than windfarms' substations
- Monitoring the temperature of additional cable circuit, Ardoch & Over Enoch
- Modification of the system architecture to meet SPEN IT security requirements and incorporation to the corporate system
- Deploying independent temperature sensors for DTS validation

There have been some modifications to the original planned approach in order to enhance the system performance. These modifications are described in the following sections:

7.1 Installation of the DTS Equipment at East Kilbride South Substation

The initial plan was to place the Distributed Temperature Sensing (DTS) hardware at the remote windfarm substations. Nonetheless, based on the Sensornet (DTS equipment supplier) proposed design, it was decided that it would be more appropriate to place the primary DTS hardware for all the cable circuits at East Kilbride South substation.

There was already an existing DTS cable temperature monitoring scheme in the telecommunications room within East Kilbride South substation that monitors the temperatures of one of the 275kV cable circuits connecting Whitelee windfarm. The existing DTS system could only provide access to the fibre temperature data locally. The control cabinet of the existing DTS system was replaced with one that can accommodate the DTS hardware of both the 275kV and 33kV cable circuits. The Whitelee 275kV cable circuit was also integrated into the new DTS system. The following advantages were expected from this modification:

1. Added ability to collect and analyse the DTS data through one central DTS server
2. Optimised the space used for the DTS control cabinets required for monitoring all the cable circuits
3. Captured and monitored the Whitelee windfarm 275kV cable temperature data in the new DTS system which allows now remote monitoring of temperature profile of Whitelee circuit and also calculating the dynamic thermal ratings of this circuit
4. Avoid risk of delays in the installation of the DTS hardware in case of any contingencies in the construction of the windfarms substations.

7.2 Monitoring the Temperature of Additional Cable Circuits

The initial scope of work defined in the project registration pro-forma included the trial of the DTS system for monitoring the temperature of three 33kV cable circuits connecting Dungavel, Calder Water and West Browncastle wind farms. In the course of the project, however, the connection of another windfarm, the Ardoch & Over Enoch windfarm, was scheduled for East Kilbride South substation via a 33kV cable circuit, which was laid in the same trench as the other three windfarm circuits. Due to the thermal impact of the other cables on the Ardoch & Over Enoch cable, it was decided to include this circuit in the DTS system. In total, four 33kV cable circuits and one 275kV cable circuit were included in the DTS system.

7.3 Modification of the System Architecture Due to IT Security

The initial system architecture was found not to comply with SPEN's security requirements. The interface between Sensornet, as a third party, to the SPEN network was considered "untrusted". Although there was network security provided by a firewall, SPEN's policy is that untrusted devices should not connect directly to the trusted network. The Sensornet devices were required to provide data to the Plant Information (PI) service that is considered critical infrastructure.

In order to modify the system to conform to SPEN's IT system security requirements, the following work was carried out:

1. All workstations initially provided by Sensornet were replaced with standard Windows 7 workstations configured by SPEN. The DTS workstation, to which the optical fibre is attached, remained on the Sensornet supplied hardware, unpatched and without antivirus protection. The DTS resides on an embedded version of Windows 7.
2. A local network was created between the DTS workstation and a "Modbus Import" server to ensure that all communications to the main SPEN network are via a managed device. The workstation that is used for the Modbus Import had two network adapters fitted: one to facilitate a private network with the DTS system and the other to the main network. Sensornet then installed the software components necessary for the DTS solution on these workstations.
3. A site-to-site VPN service was implemented between the SPEN network and Sensornet to facilitate remote support. In the initial system design it was possible to connect directly from Sensornet to the workstations at East Kilbride South substation, but it was preferred that all connections to SPEN should be terminated at a Terminal Server (termed as Jump Server). In this way all remote connections are via a central server and that domain authentication is mandated by this server.

7.4 Deploying Independent Temperature Sensors for DTS Validation

In order to validate the temperatures measured by the DTS system, independent temperature sensors, "Tinytags", were installed at different locations close to the optical fibre cables. A sensor was installed in one of the chambers, which are close to the cable routes and house the optical fibre cable junction boxes. Chambers provide a direct access to the optical fibre cables and Tinytags could be installed very close to the optical fibre cables. Another sensor was installed in East Kilbride South substation close to optical fibre loop (calibration loop) just outside the DTS cabinet. The measured data for a period of around one month were collected at East Kilbride South and Chamber 17. The comparison between the Tinytags data and the measured temperatures reported by the DTS system confirmed the accuracy of the DTS. Section 5.7 shows the results of the validation.

8 Significant Variance in Expected Costs and Benefits

The total actual expenditure is £15,304 below the initial estimated total expenditure of £710,504. There have been some variations in different expenditure elements:

- IT- £11,623 overspend due to modifications required to the workstations to meet SPEN security standards
- Labour- £40,071 overspend due to additional resources worked on modifying system architecture
- Optical fibre installation - £21,627 overspend due to including Ardoch & Over Enoch in the DTS system
- DTA and DCR Equipment - £88,624 underspend due to selecting supplier through a competitive tender

The variance in benefits of this project is due to the delay in the commissioning of Dungavel Windfarm circuit which is scheduled to be energised after Low Carbon Networks Funding (LCNF) period for this project. The delay in energisation of this circuit was only due to change in the ownership of the windfarm. This project did not fully quantify the additional headroom in the 33kV cable circuit as the actual thermal impact will appear when all 33kV circuits operate under sustained maximum generation condition. SPEN is consequently planning to continue this project by carrying out further data analysis on the cable temperature profiles for a 12-month period when all the 33kV circuits have been energised.

8.1 Variance in Costs

The initial estimated project cost, as per registration, was £710,504 and the actual project expenditure has been £695,200. Table 5 shows a summary of the project expenses for various elements. The total actual expenditure is £15,304 below the initial estimated total expenditure. There have been some variations in different expenditure elements, which are explained in the following sections.

Table 5: Forecast and actual project expenditure

Element	Forecast expenditure	Actual expenditure by March 2015	Variance	Variance (%)
IT	£20,000	£31,623	£11,623	58%
Labour	£121,192	£161,263	£40,071	33%
Optical fibre installation	£299,688	£321,315	£21,627	7%
DTS and DCR equipment	£269,624	£181,000	-£88,624	-33%
TOTAL	**£710,504**	**£695,200**	**-£15,304**	**-2%**

The project expenditures and the variances in percentage are also shown in Figure 55 and Figure 56.

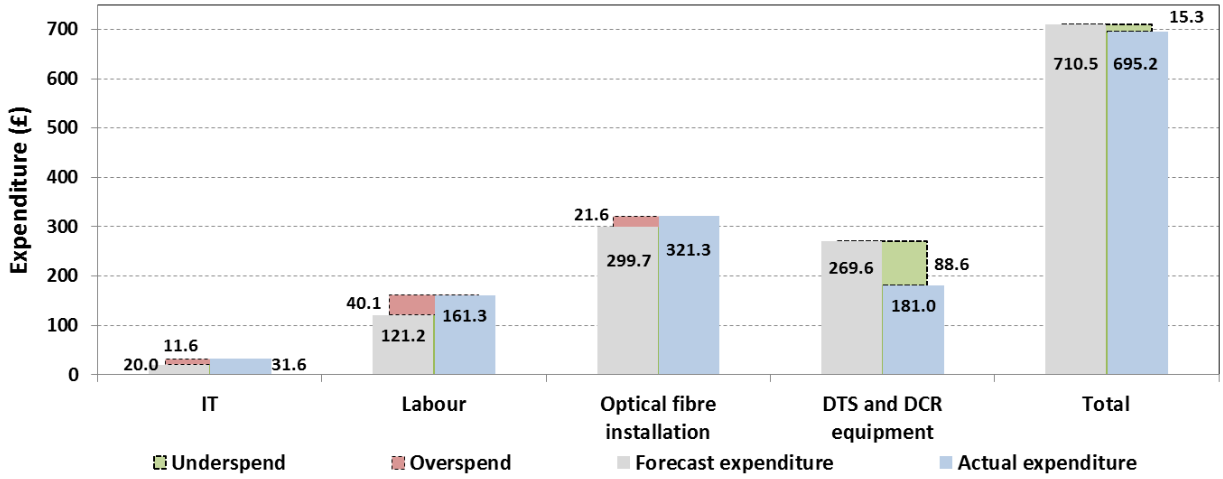

Figure 55: Project expenditure overview

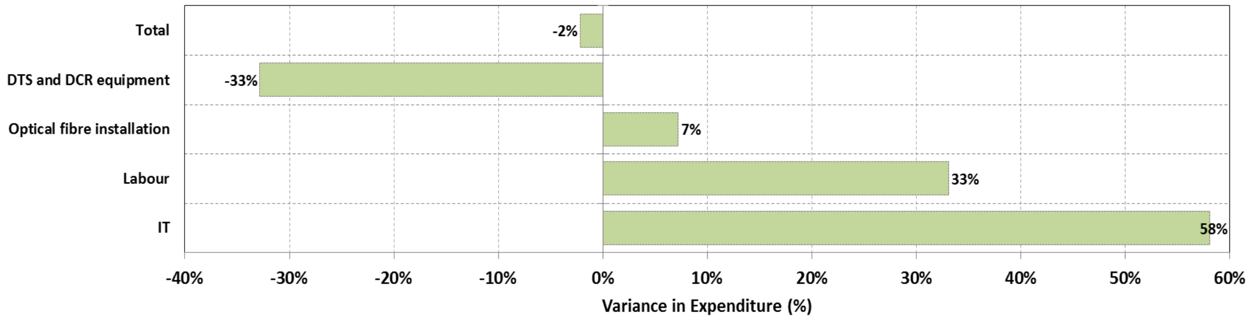

Figure 56: Variance in project expenditure

8.2 IT

The overspend in IT was due to the modifications of the system architecture that was required. The Dynamic Cable Rating (DCR) and DC-View workstations, initially supplied by Sensornet, were configured for stand-alone applications and they did not fully comply with SPEN's network security requirements. These workstations were replaced by SPEN's standard IBM workstations. Section 7.3 provides the details of the modifications implemented in the system architecture.

8.3 Labour

The extra expenditure in labour is due to the two following reasons:

- Extra time spent to implement the modifications in the system architecture and resolve the IT security issues – see section 7.3.
- Extra time spent for managing the optical fibre installation for part of the Ardoch & Over Enoch cable circuit, which shares the same trench with the other three 33kV cable circuits – see section 7.2.

8.4 Optical Fibre Installation

The final expenditure on optical fibre installations is £21,627 over the initial expenditure forecast. This is due to additional micro-ducting, optical fibre blowing and Distributed Temperature Sensing

(DTS) system calibrations carried out for the Ardoch & Over Enoch cable circuit. Section 7.2 outlines this modification to the original plan.

8.5 DTS and DCR Equipment

The expenditure on the DTS and DCR equipment was significantly lower (-£88,624) than the initial estimation. The initial market research suggested that DTS equipment should be installed at both ends of each cable circuit. However, in the procurement process, it appeared that Sensornet could supply the DTS equipment, which only needed to be installed at one end of the cable circuit for full-length coverage. The reduction in numbers of the required DTS equipment and the final equipment costs received through competitive tender process resulted in a significant reduction in the actual DTS and DCR equipment cost.

8.6 Variance in Benefits

The main benefit, initially identified for this project, was to demonstrate that there is additional headroom in the three windfarm 33kV cable circuits sharing the same trench by implementing a DCR system. The project delivered a full cable length temperature monitoring system together with a dynamic thermal calculation system. One of the 33kV circuits, however, is not scheduled to be energised until the third quarter of 2015. Consequently, due to the delay in the commissioning of all of the cable circuits, this project did not quantify the additional headroom in the 33kV cable circuits. SPEN is planning to carrying out further data analysis, in a follow-on registered Network Innovation Allowance (NIA) project, on the cable temperature profiles when all the 33kV windfarm circuits have been energised and operate under sustained maximum generation condition

The other benefit of this project is the learning delivered by trialling the cable temperature monitoring system. This trial provided real-time temperature data for the full length of the cable circuits. The cable temperature data together with concurrent loading conditions suggested that potentially the cable circuits can be assigned a higher thermal rating than the rating usually considered based on standard practices. Chapter 9 provides further details of the learning from this project.

9 Lessons Learnt for Future Projects

This project provided valuable lessons learnt from implementation of DTS and DCR systems. The key learning points are as follows:

- The installation of the optical fibre cable and micro-ducts in the centre of the trefoil cable arrangement is an effective approach to measure the surrounding temperature of the cable, i.e. the closest temperature to the cable core.
- The quality control is important to be carried out during installation with extreme care in order to avoid the need for access to the ducts and optical fibres after its completion
- The length of the installed optical fibre cable is longer than the associated power cable as additional fibres may be coiled up for calibration or spare. This additional fibre length should be deducted from DCR calculation
- The initial data analysis of the cable temperature profiles showed that the fibre temperature reaches 40 °C during highest loading conditions. Although the cable core temperature is higher than the fibre temperature, initial indications suggest that there could be still headroom to reach the 78°C maximum permissible temperature. This, however, needs to be evaluated once all the 33kV circuits are connected and sustained generation conditions are experienced.
- The temperature profile of a power cable is not flat and varies at different locations along the cable route, depending of the proximity with other circuits, surface type and depth of burial.
- The data analysis of loading of windfarms circuits showed that the actual heat dissipation levels in these cable circuits is likely to be higher than the heat dissipation levels assumed for a continuous cable loading. In other words, considering dynamic ratings, rather than continuous rating, seems more relevant for sizing the windfarm cable circuits.
- In order to ensure that third party devices comply with IT security requirements and that the vendors understand them, early IT engagement is required
- It is important to have a real-time, end-to-end diagnostics system in place to identify any source of error in the monitoring or communication equipment and remedial actions required.

The following significant issues were encountered in the course of project:

- The delay in commissioning of the Dungavel windfarms circuit did not provide visibility of the mutual thermal impact between the 33kV windfarm circuits within the lifetime of this project.
- Integration of third party equipment, which can be considered as “untrusted” to the SPEN main IT network
- The DTS equipment uses a different communication protocol from the protocol used in SPEN’s network.
- The loading of the West Browncastle Windfarm circuit was not available for DCR calculation due to communication issues between transducer and RTU.

SPEN is planning to investigate the requirement for application of a cable temperature monitoring system in an Active Network Management system (ANM) to control the output of the generators based on real-time cable ratings.

9.1 Summary of Learning

The lessons learnt from the implementation of the cable temperature monitoring system are summarised in different categories as follows:

9.1.1 Installation

1. The installation of the optical fibre cable and micro-ducts in the middle of the trefoil cable arrangement is the best approach to measure the surrounding temperature of the cable, i.e. the closest temperature to the cable core. In an alternative methodology, where the optical fibre cable is placed outside the trefoil, the optical fibre temperature may be highly affected by other parameters outside the thermal zone of the cable and consequently the measurements might be quite different from the actual cable core temperature
2. Using pre-cast fibre jointing chambers can expedite the installation process, reduce the road closure time and reduce the total cost of chamber installation
3. The quality control is an important consideration during installation in order to avoid the need for access to the ducts and optical fibres after its completion. There should be a continuous quality check in place to ensure micro-ducts are fitted in the middle of trefoil. This was identified as an important risk of the project that could potentially involve opening up of HV joint bays. In order to mitigate this risk, it was ensured that the method statement – see Appendix C: Method Statements – Cable Ducts & Micro- C – was properly communicated with the cable installation contractor.
4. The time-in-motion study carried out during installation showed that installation of the micro-duct at the time of cable duct installation does not increase to the total installation time usually required for only ducted cable installation.
5. Labelling and colour coding of micro-ducts can help avoid confusion during micro-duct installation and identify them in the event of future maintenance. It is recommended that the colours selected for micro-ducts should be different from colours used by other nearby facilities e.g. gas, water, telecoms.

9.1.2 Dynamic cable ratings

1. In this project, the initial data analysis of the cable temperature profiles showed that the fibre temperature, which represents temperature around the cable, reaches 40°C during maximum loading conditions. Based on SPEN's code of practice, the maximum permissible operating temperature for the 33kV XLPE cables is 78°C; hence, there is potentially capacity headroom before reaching the temperature limit. This, however, needs to be evaluated once all the 33kV circuits are connected and sustained generation conditions are experienced. SPEN is planning to quantify the headroom available in the 33kV cable circuits in a follow-on project after all the cable circuits have been energised.
2. The length of the installed optical fibre cable is longer than the associated power cable. This extra length can be due to the following:
    - Optical fibre cable from the DTS cabinet within the substation to where optical fibre cable joins the power cable
    - Optical fibre cable from the cable route to each optical fibre chamber and also spare optical fibre cable coiled up within these chambers and at each of circuit for calibration purposes

- Optical fibre cable snake effect within the micro-duct when using optical fibre blowing technique.

In order to provide an accurate representation of the temperature profile along the power cables and identify the exact locations of the thermal pinch points, the length of the optical fibre cable sections, which are not placed along the power cable, should be deducted from the DCR calculations.

3. The temperature profile of a power cable varies at different locations along the cable route. The temperature variations depend on various parameters, such as those listed below:
    a. Proximity to the other cable circuits
    b. Soil thermal resistivity
    c. Ground/surface type, e.g. road, river etc.
        - Depth of burial
        - Backfill material

    Deploying Distributed Temperature Sensing (DTS) systems can be an effective approach to identifying and monitoring the thermal pinch points along a cable circuit. The initial data analysis on the DTS data showed that the locations of the thermal pinch points along a cable circuit remain almost unchanged. For example, one of the thermal pinch points identified in this project was the crossing point between the Whitelee 275kV cable and the three 33kV cable circuits – see section 5.6.
4. The output power of the windfarms follow a stochastic variation that allows the cable circuits to dissipate heat gained during high wind power period. The data analysis in this project showed that the LLF[1] of the Calder Water windfarm cables are below 0.5 for around 80% of the time – see section 5.4.1. This suggests that unlike standard practice, which considers a continuous thermal rating for windfarm cable circuits, a dynamic rating can also be considered. In other words, based on typical windfarm power outputs, there is potentially an opportunity to enhance asset utilisation and therefore expedite windfarm connections by considering a firm network capacity and a non-firm network capacity. SPEN will be investigating this further by considering the loading and temperature variations of the windfarm cables for at least a 12-month period in a follow-on project.
5. The initial data analysis of the cable temperatures demonstrated a fibre temperature increase of around 8°C due to thermal effects from adjacent cables (this result is specific to this project). Based on this learning, for future cable routing, it is recommended that cables with higher loading are placed along the side of the trench rather than in the middle to allow for better heat dissipation and separation from the thermal zone effect of other cables.
6. Monitored data and calculated DCR values are crucial for further analysis and learning from the project. The systems holding the majority of the data should be located in the datacentre in order to facilitate centralised back-up.
7. In order to build confidence in the accuracy of the DTS system and the monitored optical fibre temperatures, the accuracy of the DTS system was confirmed by comparison with temperatures recorded by the independent temperature sensors that were placed at two locations accessible to optical fibres – see section 4.11.

[1] Loss load factor is used in ER-P17 for cable cyclic rating calculation

9.1.3 System reliability

1. Like most organisations, SPEN enforce strict control on the devices that interface with its network. In order to ensure that these devices comply with IT security requirements and that the vendors understand them, IT support should be actively engaged in the project from an early stage.
2. In order to enhance the IT network security, the access of a third party to the workstation interfacing SPEN's main network can be established through a Jump Server – see section 7.3
3. In order to minimise system interruptions, any unnecessary applications which may periodically check for updates should be removed from the workstations. The best practice is that Dynamic Cable Rating (DCR) applications should run as a Windows service and not as a user application
4. It is important to have a real-time, end-to-end diagnostics system in place to identify any source of error in the monitoring or communication equipment and remedial actions required.

9.2 Recommendations on How the Outcome of the Project can be Exploited Further

The outcomes of the project can be further exploited by:

1. Validating the cable rating assumptions and modifying the future cable rating calculation
2. Informing future cable route planning
3. Using the DTS system for fault location applications
4. Estimating the thermal pinch points in existing cable circuits and allocating the temperature sensors retrofitted at hot spots, if possible.
5. Using the historical data for research purposes
6. Estimating the firm and non-firm connection capacity for future generation connection applications
7. Informing an active network management system to control the generator output based on the real-time available network capacity
8. Providing learning to staff and planning properly for identifying DTS and DCR assets ownership in a future business as usual application.
9. Providing learning from this project to other cable circuit which are monitored by using DTS system e.g. Western Link

9.3 Discovery of Significant Problems

The following significant issues were encountered in the course of project:

1. The delay in connection of the Dungavel windfarms did not allow the full impact of the DTS system within the lifetime of this project. The 33kV Dungavel windfarm cable circuit is due to be commissioned in the third quarter of 2015. SPEN is planning to continue this project by carrying out further data analysis on the cable temperature profiles when all the 33kV circuits have been energised and loaded under sustained maximum generation conditions. Integration of third party equipment, which can be considered as "untrusted" to the SPEN main IT network. Sensornet equipment did not fully comply with SPEN's network security

requirements and therefore the system architecture and configuration of the workstations were modified.

2. The DTS equipment uses a different communication protocol from the protocol used in SPEN's network. In order to establish accurate communication data between DTS and DCR workstations, a file transfer approach was used.
3. There was a problem in communication between transducer and RTU for West Browncastle circuit at East Kilbride substation. As a results of that the current, voltage and power of the West Browncastle circuit were not available for DCR calculations. This issue was recently resolved after updating the transducer firmware.

9.4 Future Deployment of DCR on a Large Scale

SPEN is planning to investigate the requirement for the application of a cable temperature monitoring system in an active network management system to control the output of the generators based on real-time cable ratings.

As one of the outcomes of this project, it is recommended that micro-ducting is considered as a business as usual practice as part of future cable installations. This facilitates the implementation of a DTS system in the future, if required.

9.5 Effectiveness of Contractual Methods

In this project Sensornet was awarded the contract and Bandweaver Ltd and Alquist Consulting Ltd were subcontractors to Sensornet. This contractual method, with a single point of contact, was considered to be an effective approach in terms of overall project management and communications when different vendors are involved in a project.

10 Planned Implementation

The results and learning from this project demonstrated that both SPEN and windfarm connection customers could benefit from deploying a real-time cable temperature monitoring system. Scottish Power Energy Networks plan to conduct a new project under the Network Innovation Allowance (NIA) funding mechanism to prepare DTS and DCR system for full business adoption. The new NIA project has been registered as "Enhanced real-time cable temperature monitoring" (NIA_SPEN0003). The following developments have been considered in this new NIA project:

- Data analysis of a 12-month period
- Requirements for integration DTS and DCR into an Active Network Management (ANM) system architecture
- Developing policy documents and technical specifications for future DTS and DCR systems for Business as Usual application

In addition, the implemented cable temperature monitoring system can be further enhanced by considering following developments:

- Deploying for fault location application
- Defining ownership of the system and maintenance required
- Installation of micro-duct during power cable installation
- Deployment of independent temperature sensors at possible cable hot spots

The results and learning from this project demonstrated that both the SPEN and windfarm connection customers could benefit from deploying a real-time cable temperature monitoring system. Scottish Power Energy networks plan to continue this project under the Network Innovation Allowance (NIA) funding mechanism to prepare Distributed Temperature Sensing (DTS) and Dynamic Cable Rating (DCR) systems for full business adoption. The trialled systems can be further developed as follows:

Data analysis for a 12-month period: In order to boost confidence in the implemented DTS system and fully capture the thermal behaviour of the cable circuits, the real-time temperature data should be studied for a at least a 12 month period to cover different weather conditions and different loadings of the cable circuits. SPEN plan to carry out analysis of the real-time cable temperature data over a period of a full year under a new NIA project.

Integration to an ANM system: The actual benefit of deploying a real-time cable temperature monitoring system materialises in an active network management (ANM) application where the outputs of generators are controlled based on the available real-time network capacity. For full adoption of this ANM system, an end-to-end solution covering from the design stage to day-to-day operation should be provided. SPEN plan to investigate a practical approach for integrating the DTS system into an ANM system. SPEN has previously trialled an ANM system which uses static cable ratings; the further enhancement to this system will be informing the ANM system with a real-time cable rating.

Fault location application: The provision of a full-length thermal profile of the cable circuits could be used to speed up locating the faults occurred at any point of the cable circuit. SPEN will explore the best approach for adapting this application within the business.

Ownership of the system: As part of the full adoption of the DCR system in the business as usual, the ownership of this system and responsibility for any maintenance and expansion should be clearly defined within the business. SPEN will be internally discussed this matter with different stakeholders to identify the appropriate future ownership of the DCR system within SPEN.

Installation of micro-duct in the time of power cable installation: It is recommended that micro-duct installations are considered as part of normal practice for power cable installation. This provides flexibility for any future DTS or other application where optical fibre cable can be blown if required.

Deployment of the independent temperature sensors at the possible hot spots: Data analysis on the historical variation of the cable temperature will provide valuable information and learning for estimating the locations of the hotspots in other cables where a DTS system has not been installed. Based on this learning, retrofit temperature sensors can be planted in critical locations, where it is possible, to enhance the thermal visibility on the cable circuits.

11 Facilitate Replication

The cable temperature monitoring system trialled in this project is completely replicable in a new cable installation. The knowledge required to replicate the real-time cable temperature monitoring system includes:

- DTS system design methodology
- DTS system equipment specifications
- Optical fibre cable and micro-ducting installation methodology
- IT and telecommunications expertise
- Cable thermal modelling methodology
- Cable rating standards, technical papers and presentations

The products required to replicate the real-time cable temperature monitoring system can be categorised as follows:

- Monitoring equipment
- Communications and IT equipment

The services required to replicate the DTS system may be delivered by different organisations listed below:

- the DNO (or consultancy acting on the DNO's behalf)
- the monitoring equipment supplier
- the DCR thermal modelling provider
- micro-ducting and optical fibre installation provider

The following points of contacts are also available for any query with regard to replication of the DTS and DCR systems:

- Geoff Murphy, SP Energy Networks (Geoff.Murphy@sppowersystems.com)
- David Ruthven, SP Energy Networks (DRuthven@scottishpower.com)

The cable temperature monitoring system trialled in this project is completely replicable. In order to replicate the real-time cable temperature monitoring system implemented in this project the following knowledge, data, products and services are required.

11.1 Knowledge Required to Replicate the Dynamic Cable Rating System

The knowledge required to replicate the real-time cable temperature monitoring system is outlined below:

- DTS system design methodology
- DTS system equipment specifications
- Optical fibre cable and micro-ducting installation methodology
- IT and telecommunications methodology
- Cable thermal modelling expertise
- Cable rating standards, technical papers and presentations

11.1.1 Industry standards

For better understanding of the thermal behaviour of the cable circuits and the industry's business as usual practice for cable rating calculations, awareness of the following industry standards and engineering recommendations would be a prerequisite:

- IEC 60287: "*Electric Cables – Calculation of the Current Rating*"
- IEC 60853: "*Calculation of the cyclic and emergency current rating of cables*"
- Engineering Recommendation P17 (Part 1, Part 2 and Part 3): "*Current Ratings for Distribution Cables*"

11.1.2 Other publications

Publications providing techniques for modelling the thermal behaviour of the cable based on the surrounding temperature and publications describing the DTS technology can provide the principle required knowledge. The recommended publications include:

- F. M. Echavarren, L. Rouco and A. González: "*Dynamic Thermal Modelling of Insulated Cables*", B1-209, CIGRE, 2012
- Abhisek Ukil, Hubert Braendle and Peter Krippner: "*Distributed Temperature Sensing: Review of Technology and Applications*", IEEE Sensors Journal, 2011

11.2 Summary of Intellectual Property Rights (IPR)

A summary of background IPR and relevant foreground IPR is given in Table 6.

Table 6: Background and relevant foreground IRP

Background IPR	IPR Type	Access
DC-View software	Background	via Alquist Ltd
DCR software	Background	via Bandweaver Ltd
DTS equipment	Background	via Sensornet Ltd
Optical fibre and cable temperature data	Foreground	via Scottish Power Energy Networks

11.3 Data Required to Replicate the Cable Temperature Monitoring System

A summary of the input and output data required for replicating the cable temperature monitoring system is as follows:

Input datasets

- Geographical information and mapping of the cable routes
- Distance between buried cable circuits and cable configuration
- Electrical parameters of the cable circuits
- Maximum permissible operating temperature
- Parameters of the equivalent thermal models of the cables
- Real-time loading of the cable circuits
- Location of the optical fibre jointing chambers

Output datasets

- Real-time optical fibre temperature profile along the cable circuits
- Real-time calculated temperatures of the conductor cores and other cable layers
- Location of the thermal pinch points along the cable circuits
- Dynamic thermal ratings of the cables in the form of Short-Term Permissible Loadings and Short-Term Permissible Durations
- Circuit utilisation statistics
- Independent temperature sensor data

11.4 Products Required to Replicate the Cable Temperature Monitoring System

The products required to replicate the real-time cable temperature monitoring system can be categorised as follows:

- Monitoring equipment
- Communications and IT equipment

11.4.1 Monitoring equipment

- DTS equipment including multiplexer and associated workstations
- Sensing cable (optical fibre cable) and micro-duct
- Current transformer (CT) measuring the circuit loading
- Independent temperature sensors for DTS accuracy validation

11.4.2 Communications and IT equipment

- Network switches and protocol converter
- Intermediate IT equipment and approved servers to ensure safe connectivity and security of system, if necessary
- Keyboard, mouse and visual (KVM) equipment for carrying out on-site system setup, diagnostic measures
- Uninterruptible power supply (UPS)
- Reliable hardwired communication with the DNO IT network
- DTS workstations configured based on DNO IT security standards
- DCR workstation and software
- Data visualisation applications e.g. DC-View application

11.5 Services Required to Replicate the Cable Temperature Monitoring System

The services required to replicate the DTS system may be delivered by different organisations listed below:

- the DNO (or consultancy acting on the DNO’s behalf)
- the monitoring equipment supplier
- the DCR thermal modelling provider
- Micro-ducting installation and optical fibre blowing provider

Depending on the policy of the DNO, some of these services could be provided in-house. Depending also on the tender and the contract award, a complete solution could be provided by a sole supplier.

11.5.1 DNO

The following services are required by the DNO (or consultant acting on the DNO's behalf):

- Project management
- Site identification and system requirements
- Financial analysis and business case development
- System architecture design
- IT System security evaluation based on DNO security requirements
- Equipment specifications evaluation
- Procurement
- Equipment storage facility
- Installation supervision, maintenance and commissioning
- Witnessing of FAT and SAT

11.5.2 DTS Monitoring Equipment provider

In addition to supplying the equipment, the following services could be provided by the monitoring equipment provider:

- DTS Equipment installation
- Carrying out of the necessary FAT and SAT
- DTS system calibration
- Modification of the system architecture as required for integration into the corporate system
- Training, maintenance and diagnostic services

11.5.3 DCR and software provider

The following services could be provided by the DCR provider:

- Provision of approved thermal models of the cable circuits
- Provision of approved calculation methodology for dynamic cable rating
- Provision of a user-friendly interface for visualising the results
- Carrying out of the user acceptance test

11.5.4 Micro-ducting and optical fibre blowing provider

Micro-ducting and optical fibre installation should take place at the same time as power cable installation and the following services are required:

- Micro-duct installation
- Optical fibre blowing into the micro-duct
- Carrying out of the Optical Time Domain Reflectometer test and the Site Acceptance test
- Carrying out of optical fibre jointing (fusion splicing)
- Support with DTS optical fibre calibration tests

11.6 Summary of Points of Contact

The following points of contact are available to provide further details on the cable temperature monitoring system implemented in SPEN's Tier 1 LCNF "Temperature monitoring windfarms cable circuits":

- Geoff Murphy, SP Energy Networks (Geoff.Murphy@spenergynetworks.com)
- David Ruthven, SP Energy Networks (DRuthven@scottishpower.com)

Appendices

Appendix A: LCNF First Tier Registration Pro-forma

Appendix B: Equipment Specification

Appendix B1: DTS Equipment specifications

Appendix B2: Micro-duct specifications

Appendix B3: Sensornet Manual

Appendix C: Method Statements – Cable Ducts & Micro-Ducts

Appendix D: Datasets

Example of optical fibre temperature measurements (Calder Water)