SP ENERGY NETWORKS

Implementation of Real-Time Thermal Ratings

Final Close Down Report

SPT1001 Implementation of a real-time thermal rating system on the 132kV network in North Wales

PARSONS BRINCKERHOFF

LCN Fund Low Carbon Networks

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Executive Summary

Project Background

Scottish Power Energy Networks (SP Energy Networks) was a partner with the University of Durham, AREVA T&D, Imass and Parsons Brinckerhoff in an Innovation Funding Incentive (IFI) / Technology Strategy Board (TSB) funded research and development (R&D) project to design and install a real-time thermal rating (RTTR) system for overhead lines, cables and power transformers on a test network in North Wales. In this R&D project, an active thermal controller (combining RTTRs with a distributed generation (DG) output control system) was developed, prototyped and validated. The field trial data was collected and analysed and the R&D phase of the project came to an end in March 2010.

This project was the recipient of the Institution of Engineering and Technology (IET) Innovation Award in the Power / Energy Category in 2010.

Through the Low Carbon Networks Fund (LCNF), SP Energy Networks has collaborated with Parsons Brinckerhoff, GE Energy, Nortech Management Ltd and Skye Instruments to build on the IET Innovation Award-winning work of the previous project and deploying an RTTR system that covers more than 90km of the existing North Wales distribution network. SP Energy Networks' RTTR system utilises a cost-effective thermal state estimation (TSE) with integrated sensors approach. A meshed network of weather stations, together with a detailed geographical model, allows the thermal ratings of the overhead line network to be calculated in real-time. The RTTRs can be validated against a limited number of conductor temperature sensors, carefully selected to minimise the number and duration of outages required for equipment installation. The RTTR system has been embedded within SP Energy Networks' Network Management System (NMS) as a discrete module.

Scope and Objectives

The key objectives of this project were to:

- Release network capacity for 132kV wind generation;
- Provide SP Energy Networks' control room with complete thermal visibility of the North Wales 132kV overhead line network from Connah's Quay to Pentir;
- Gain business confidence to offer active network management (ANM) solutions for prospective generation customers, as part of a RTTR system.

Success Criteria

The following success criteria were identified in the original Project Registration Pro-forma:

1. Install the necessary equipment to support an open-loop control system infrastructure to facilitate the connection of embedded generation;
2. Prove the integrity of the RTTR technology embedded within PowerOn Fusion Network Management System (NMS) through data analysis of 1-year's operation as a minimum;
3. Build the confidence of SP Energy Networks to adopt the technology;
4. Ensure that network integrity and security of supply are not compromised during all stages of the project;

5. Provide accurate documentation to facilitate change control through the course of the project (for example, changes in staff working on project).

Details of the Work Carried Out

The following trialling methodology was used in this project to deploy the RTTR system across North Wales:

1. Identify current or expected thermal pinch points in the network and establish the project location;
2. Specify the most appropriate RTTR system to deploy;
3. Survey the network and specify equipment monitoring locations;
4. Design the system architecture and establish a set of factory acceptance and site acceptance tests;
5. Procure, install and commission the RTTR system equipment;
6. Gather data, analyse the system performance, carry out maintenance and remedial work (as required);
7. Capture lessons learnt during deployment and provide recommendations for moving towards business adoption.

The implementation of this methodology allowed data to be gathered for a 12-month period to understand the gains from the RTTR system through the complete operational year and to observe the reliability of the system through on-line inspection and off-line data analysis.

Project Outcomes

The following outcomes resulted from this project:

1. Ten weather stations, and the associated information and communication technologies, were successfully installed across 90km of North Wales to implement the RTTR system;
2. Data from the ten weather station installations was used to calculate the RTTR of eight circuits for the twelve-month period from 24th September 2012 to 23rd September 2013;
3. The data can be seen on live displays in SP Energy Networks' control room and via web interfaces at locations remote to North Wales, within the UK. In addition, the data is stored within a data historian for offline analysis;
4. For the twelve-month period, it was shown that the average uplifts ranged from 1.24 to 1.55 times the static summer rating. The potential average additional annual energy yield ranged from 10% to 44% for the circuits considered.

Project Performance against Objectives and Success Criteria

Objectives

This project succeeded in delivering outputs to fulfil the original project objectives:

- The project has demonstrated the potential capacity that can be unlocked within eight circuits of a 132kV distribution network, through the practical implementation of a RTTR system;
- Prior to this project, SP Energy Networks had limited real-time visibility of the thermal status of the distribution network. This project has delivered a RTTR system that provides SP

Energy Networks' control engineers with enhanced thermal visibility of the 132kV network between Connah's Quay and Pentir;

- The prototype RTTR system, developed in the fore-running project (Active Management of Distributed Generators Based on Component Thermal Properties), was deployed on a 7km section of 132kV distribution network. This project delivered a system that calculated RTTRs within the 90km area from Connah's Quay to Pentir;
- The implementation involved the installation of meteorological stations, the data from which was processed to display RTTRs on a graphical user interface within the distribution network control room;
- A Business Adoption Strategy was developed as part of the RTTR system trial and is soon to be implemented by SP Energy Networks. Furthermore, SP Energy Networks are planning a follow-on project, focused on ANM in readiness for the accommodation of prospective generation connection applications.

Success Criteria

The project performance was evaluated against its original success criteria. Criteria 1, 3, 4 and 5 were achieved within the three-year project duration and Criterion 2 was achieved by October 2013 (within 3 months of submission of the initial Close Down Report):

1. The following equipment was successfully installed as part of the RTTR control system infrastructure: (i) ten weather station nodes (six substation-mounted and four tower-mounted units); (ii) ten RTUs for data communication; (iii) one RTU master; one RTTR server; (iv) communications systems for data transfer within SP Energy Networks. The RTTR system would have benefited from the installation of conductor temperature monitoring equipment to provide further validation of the RTTR system behaviour. However, due to supply chain issues and outage constraints, this element of the project did not take place;
2. Four quarterly reports have been generated, using data analysis techniques to demonstrate the integrity of the RTTR system embedded within the PowerOn Fusion Network Management System for an entire operational year;
3. Building SP Energy Networks' confidence to adopt the technology was achieved, recognising that RTTR systems should be deployed with ANM control systems to utilise capacity gains and control power flows at times of high generation and low thermal ratings. A Business Adoption Strategy was developed as part of the RTTR system trial and is soon to be implemented;
4. Network integrity and security of supply were not compromised at any stage during the project;
5. Accurate project documentation was maintained by Parsons Brinckerhoff on behalf of SP Energy Networks throughout the project. The project and project management process was independently audited by DNV in October 2012, which helped to maintain Parsons Brinckerhoff's ISO 9001, 14001 and 18001 accreditation.

Required Modifications

The following modifications were required during the course of the project:

1. Increased number of weather stations;
2. Development of tower-based weather station units;
3. Tower-based weather station design;
4. Weather station installation methodology;
5. Modifications to algorithm inputs;
6. Evolution to the deployment of a graceful degradation algorithm.

Significant Variance in Costs and Benefits

Variance in Costs

The original project cost was £450,000, whereas, the actual project cost £620,000 (+37%). The Project Registration Pro-forma was re-submitted in 2013 and the project was delivered within the revised budget (£620,000). The additional £170,000 in project costs was necessary expenditure and arose from:

1. The variation in contracts for weather stations and access equipment (£37,000), due to an increased number of weather stations required for system deployment to provide a sufficiently confident level of thermal visibility of the network;
2. The costs that were required to develop IT systems that were compliant with SP Energy Networks' existing policies (£80,000);
3. Additional SP Energy Networks labour (£51,000) due to increased requirements for field staff to deploy the weather stations and IT equipment.

Variance in Benefits

The previous research and development (R&D) project reported the range of theoretical average uplifts that could be achieved through deployment of overhead line RTTR systems as 1.70 to 2.53 times the static summer rating. Furthermore, the additional annual energy yield from distributed generation that could potentially be accommodated through deployment of an RTTR was found to be 20 – 54% for the cases considered.

This LCNF project has built on the R&D project to establish the practical exploitable headroom that could be unlocked through a wide-scale deployment of RTTR systems. It was found that the average uplifts ranged from 1.24 to 1.55 times the static summer rating. The potential average additional annual energy yield ranged from 10% to 44% for the circuits considered.

These results are highly encouraging and demonstrate the potential merit of RTTR system deployments. The practical exploitable headroom and energy yields values are lower than the theoretical values. This is because the RTTR system deployed in the LCNF project takes into account constraints such as cable ratings and protection equipment ratings. For business acceptance, safety margins were introduced and estimates on the side of caution were refined, in comparison to the R&D project.

Lessons Learnt

Key Learning Points in Deploying RTTR Systems

1. The importance of incorporating graceful degradation algorithms within the monitoring and control system to deal with equipment failure, communications interruptions and erroneous data;
2. The balance of centralised and distributed intelligence, and using distributed intelligence to report back information (not just data);
3. The use of multiple vendors for equipment supplies.

Recommendations for other Projects

1. The reliability of communications systems should not be taken for granted and should not be assumed to be 100%, particularly with GPRS systems;
2. End-to-end diagnostics should be designed into the system so that sources of error (equipment outages, communications outages and data outages) can be identified and pinpointed promptly, triggering remedial actions within suitable timescales;
3. Budgeting should cover the whole project lifecycle (TotEx: CapEx, OpEx, decommissioning costs) and, in particular, incorporate 'spare' equipment.

Planned Implementation

The following work is planned to develop the RTTR system further: (i) temperature sensor deployment, followed by further validation; (ii) development and deployment of refined graceful degradation algorithms; (iii) forecasting RTTRs (up to 8 hours ahead for the emergency return to service plan); (iv) quantification of RTTR uplifts through different seasons; (v) quantification of additional capacity to accommodate generation farm connections; (vi) design of an ANM scheme to control the power output of generation utilising the SCADA-based RTTR for each circuit; and (vii) exploring RTTRs for contingency (N-1 and N-2) operation.

Facilitate Replication

The knowledge required to replicate this project is contained within this report and the publications listed in Appendix B.

The products required to replicate the RTTR system can be categorised as (i) weather stations; (ii) monitoring equipment; (iii) communications equipment; and (iv) information technology equipment.

The services required to replicate the RTTR system may be delivered by a consortium, which includes: (i) the DNO (or consultant acting on the DNO's behalf); (ii) the weather station / monitoring equipment supplier; (iii) the communication solution provider; and (iv) the information technology system supplier.

It is recommended that any DNO looking to replicate this Method of RTTR system deployment should use the category guidelines as given in the Facilitate Replication section of this report for building up project lifecycle cost estimates (capital expenditure, O&M expenditure, decommissioning costs).

1 Project Background

Scottish Power Energy Networks was a partner with the University of Durham, AREVA T&D, Imass and Parsons Brinckerhoff in an Innovation Funding Incentive (IFI) / Technology Strategy Board (TSB) funded research and development project to design and install a real-time thermal ratings system for overhead lines, cables and power transformers on a test network in North Wales. The field trial data was collected and analysed and the R&D phase of the project ended in March 2010.

In this LCNF project, Scottish Power Energy Networks has worked with Parsons Brinckerhoff, GE Energy, Nortech Management Ltd and Skye Instruments to deploy a real-time thermal rating system that covers more than 90km of the existing North Wales distribution network, providing the connection point for several prospective wind farm developments.

1.1 Project Overview

Scottish Power Energy Networks (SP Energy Networks) has worked with Parsons Brinckerhoff, GE Energy, Nortech Management Ltd and Skye Instruments to deploy a real-time thermal rating (RTTR) system that covers more than 90km of the existing North Wales distribution network, providing the connection point for several prospective wind farm developments.

The RTTR system delivered more potential applications than originally envisaged: as well as the accommodation of generation connections, the RTTR system could be adapted for accommodating load growth (when deployed with a suitable demand-side management system) as well as securing supplies to customers in the event of power system outages.

The original Project Registration Pro-forma is given in Appendix A1.

1.2 R&D Phase

SP Energy Networks was a partner in an Innovation Funding Incentive (IFI) / Technology Strategy Board (TSB) funded research and development (R&D) project with the University of Durham, AREVA T&D (now Alstom Grid), Imass (now Astrium) and Parsons Brinckerhoff to design and install an RTTR system for overhead lines, cables and power transformers on a test network in North Wales. The field trial data was collected and analysed and the R&D phase of the project has now come to an end. The initial R&D phase of the project concentrated on a small part of SP Energy Networks' 132kV network that connects Rhyl to St Asaph. This network is shown in Figure 1-1.

An active thermal controller was designed, which included a thermal state estimation engine (based on thermal modelling of overhead lines, electric cables, and power transformers), a load flow routine and an intelligent control algorithm to provide automatic dispatch signals to the generators under its control. The original funding from the UK government's Technology Strategy Board ended on 31st March 2010. By March 2010 the prototype active thermal controller was running in open loop on a small section of SP Energy Networks' network between Rhyl and St Asaph. Analysis from the open loop field trial was based on two months of data harvested from the trial network.

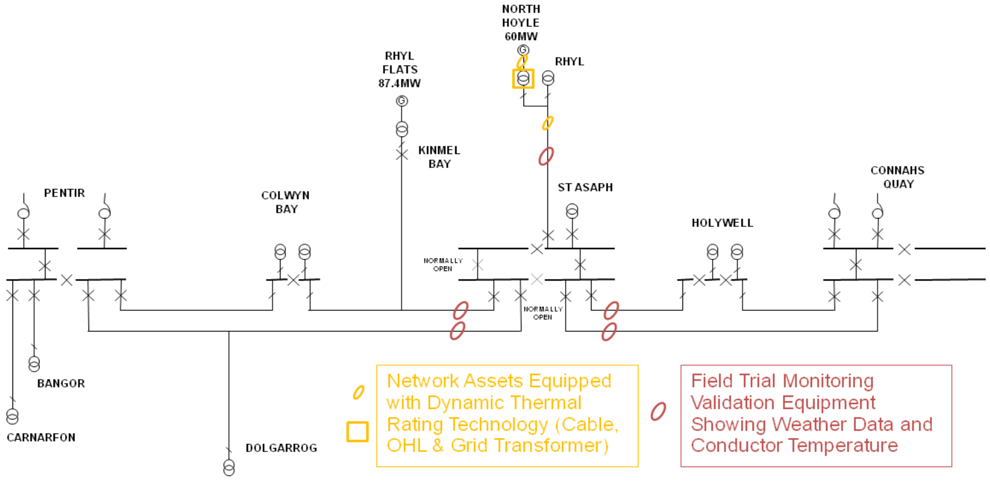

Figure 1-1 R&D Trial Network (Rhyl – St Asaph)

The location was selected because the overhead line infrastructure could represent thermal pinch points in the network and become a barrier to future prospective generation connections. This provides a genuine need-case for innovative methods (RTTR systems) to enable more cost-effective and quicker generation connections, avoiding the cost and time constraints associated with network reinforcement.

Real-time thermal ratings (RTTRs) are defined as a time-variant rating that can be practically exploited without damaging components or reducing their life expectancy. Actual measurements of environmental conditions (wind speed, wind direction, ambient temperature and solar radiation) are used as the input to steady-state thermal models.

In order to calculate and exploit the RTTR, it is assumed that local environmental condition measurements are available. Short-term transients, taking into account the thermal capacitance of power system components, are not included within the RTTR assessment. This is termed a 'dynamic thermal rating' and it is felt that this would not materially affect the GWh/annum throughput of energy within the electrical power system.

RTTR deployments could be particularly beneficial for wind farm connections since there is a correlation between the power output of wind farms at times of high wind speed and the cooling effect of the wind on overhead line conductors.

This project was the recipient of the Institution of Engineering and Technology (IET) Innovation Award in the Power / Energy Category in 2010.

2 Scope and Objectives

The key objectives of this project were to:

- Release network capacity for 132kV wind generation;
- Provide SP Energy Network's control room with complete thermal visibility of the North Wales 132kV overhead line network from Connah's Quay to Pentir;
- Gain business confidence to move forwards to offering active network management (ANM) solutions for prospective generation customers.

Renewable generation is often connected in rural locations where there is limited spare capacity within distribution networks. This project aims to unlock extra capacity in the networks, thus reducing reinforcement requirements and connection costs for wind generators.

The scope of this project is to implement an RTTR system for overhead lines that gives the control room operators greater visibility of the actual thermal operating status of their network.

The objective is to deliver the first active distribution network-based implementation of this technology across a wide area of the network. The implementation will involve the installation of meteorological stations and monitoring equipment, the data from which will be processed to display RTTRs and conductor operating temperatures on a graphical user interface within the distribution network control room.

Through open-loop analysis of the RTTR system, and confidence-building in the technology adoption, the system will then feed into an ANM project, which will facilitate and manage the connection of wind farms within congested networks.

3 Success Criteria

The following success criteria were identified in the original Project Registration Pro-forma:

1. Install the necessary equipment to support an open-loop control system infrastructure to facilitate the connection of embedded generation;
2. Prove the integrity of the real-time thermal rating technology embedded within PowerOn Fusion Network Management System (NMS) through data analysis of 1-year's operation as a minimum;
3. Build the confidence of SP Energy Networks to adopt the technology;
4. Ensure that network integrity and security of supply are not compromised during all stages of the project;
5. Provide accurate documentation to facilitate change control through the course of the project (e.g. changes in staff working on project).

4 Details of Work Carried Out

The following trialling methodology was used in this project to deploy the RTTR system across North Wales, where there is a clear business need for RTTR systems:

1. Identify current or expected thermal pinch points in the network and establish project location;
2. Specify the most appropriate RTTR system to deploy;
3. Survey the network and specify equipment monitoring locations;
4. Design the system architecture and establish a set of factory acceptance and site acceptance tests;
5. Procure, install and commission the RTTR system equipment;
6. Gather data, analyse the system performance, carry out maintenance and remedial work (as required);
7. Capture lessons learnt during deployment and provide recommendations for moving towards business adoption.

The implementation of this methodology allowed data to be gathered for a 12-month period to understand the gains from the RTTR system through the complete operational year and to observe the reliability of the system through on-line inspection and off-line data analysis.

4.1 Justification of the Planned Approach

SP Energy Networks has built on the IET Innovation Award winning work of the previous R&D phase of this project (funded through IFI and the TSB). In the previous R&D project, an active thermal controller (combining RTTRs with a distributed generation (DG) output control system) was developed, prototyped and validated.

SP Energy Networks' RTTR system utilises a thermal state estimation (TSE) with integrated sensors approach, based on the output of the previous R&D project. This cost-effective approach uses a meshed network of weather stations together with a detailed geographical model that allows the weather conditions at every span within the 90km overhead line network to be interpolated. The RTTR and operating temperature of each span of the overhead line network is calculated. The system identifies the span within each circuit that has the lowest rating and this is used to provide the rating for the entire circuit. The operating conditions of the identified critical spans can be validated against a limited number of conductor temperature sensors, carefully selected to minimise the number and duration of outages required for equipment installation.

By modelling the entire system, the DNO is provided with complete thermal visibility of the overhead line network. The meshing of weather stations allows the system to degrade gracefully, thereby making increasingly conservative estimates of the overhead line thermal ratings as an increasing number of input signals are lost. Furthermore, the integration of the RTTR system with an ANM system mitigates the risk of excessive thermal excursions at times of low thermal rating through power flow control techniques. This functionality is vital for the future integration of low carbon generation sources such as wind farms.

The solution consists of a number of weather stations that were integrated into the SCADA system and Network Management System (NMS), together with the necessary NMS hardware / software to facilitate this. IEC TR61597 and CIGRE WG22.12 standard-based algorithms are combined with thermal state estimation techniques to calculate overhead line RTTRs, based on weather data. This has been embedded within the NMS as a discrete RTTRs module.

4.2 Trialling Methodology

The following trialling methodology was used in this project to deploy the RTTR system across North Wales:

1. Identify current or expected thermal pinch points in the network and establish project location;
2. Specify the most appropriate RTTR system to deploy;
3. Survey the network and specify equipment monitoring locations;
4. Design the system architecture and establish a set of factory acceptance and site acceptance tests;
5. Procure, install and commission the RTTR system equipment;
6. Gather data, analyse the system performance, carry out maintenance and remedial work (as required);
7. Capture lessons learnt during deployment and provide recommendations for moving towards business adoption.

Steps 1 -5 of this methodology are outlined in the sections that follow. The output of Step 6 is given in Section 5 of this report. The output of Step 7 is given in Sections 9, 10 and 11.

The implementation of this methodology has allowed data to be gathered for a 12-month period to understand the gains from the RTTR system through the complete operational year and to observe the reliability of the system through on-line inspection and off-line data analysis.

4.3 Project Location

The project location extends from Pentir in the west to Connah's Quay in the east and encompasses 90km of 132kV electricity network infrastructure. The network diagram is given in Figure 4-2, and a geographical depiction is given in Figure 4-3.

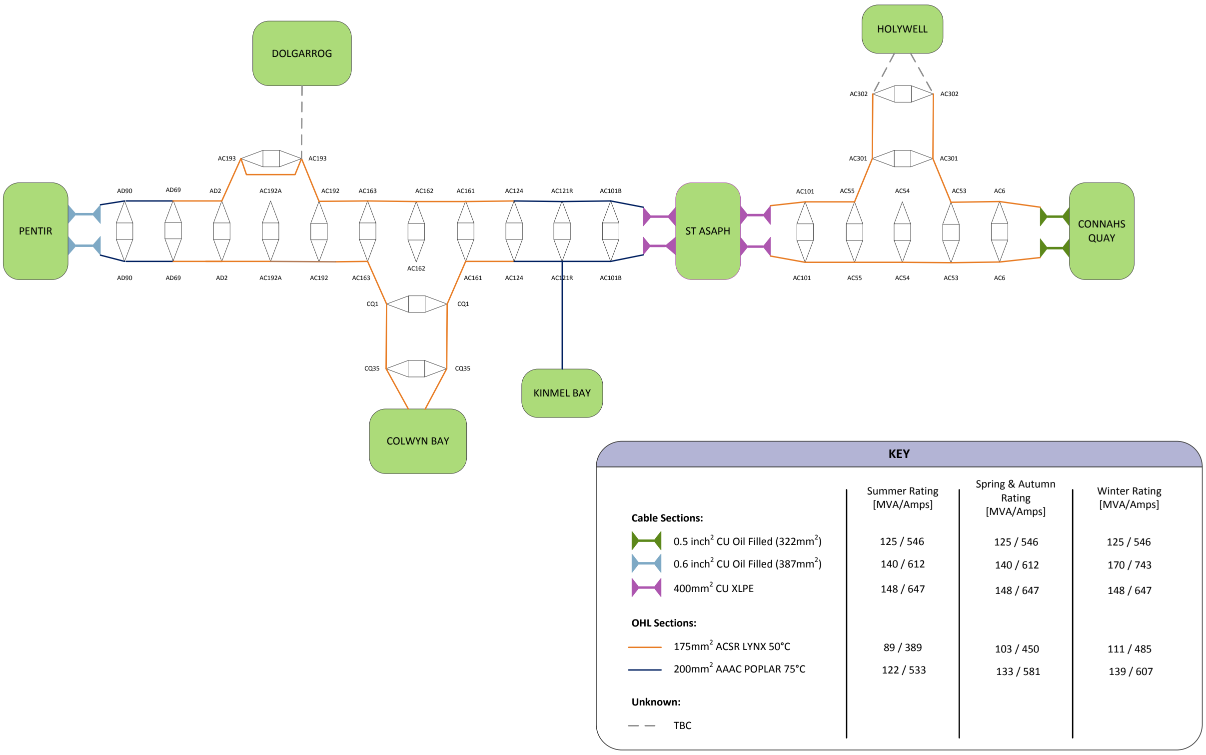

Figure 4-2 Implementation Network (East – West Interconnector)

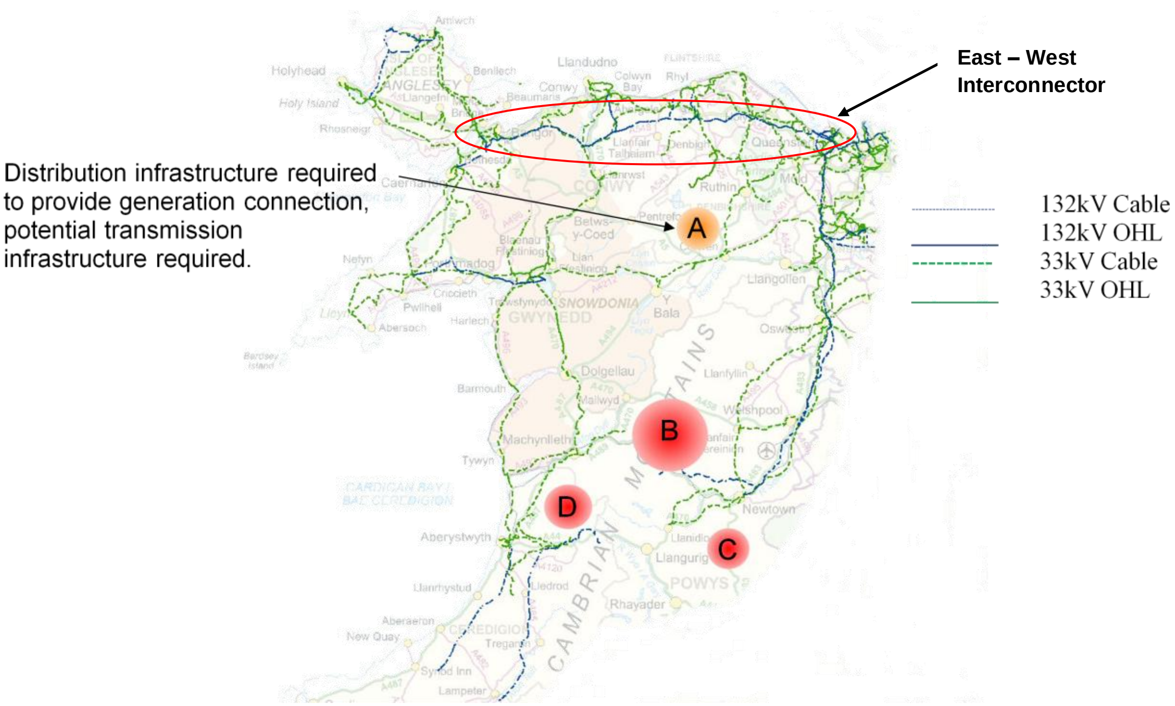

Figure 4-3 Geographical location of prospective generation in North Wales

The network covers a rural location with a number of small load centres and a large capacity of renewable embedded generation connected into both the 33kV and 132kV networks. There is approximately 150MW of wind and hydro generation connected to the 33kV network in North Wales and 150MW of offshore wind generation connected to the 132kV network. The main load centre is at Connah's Quay and the direction of power flow from the generation is predominantly from west to east.

The 132kV overhead line infrastructure is predominantly 'Lynx' ACSR 175mm^2 conductors, tensioned to operate up to a maximum conductor operating temperature of 50°C. These conductors have a conventional static summer rating of 89MVA and a winter rating of 111MVA. The Lynx conductors are scheduled for replacement with 'Poplar' AAAC 200mm^2 conductors, tensioned to operate at maximum conductor temperatures of 65°C – 75^{o}C.

4.4 Literature Survey on the State of the Art of RTTR Technologies

RTTRs have the potential to offer a cost-effective alternative to network reinforcement for Distribution Network Operators looking to accommodate load growth or distributed generation connections. In the early stages of the project, a review of the state of the art regarding RTTR technologies around the world was conducted. Focusing on overhead lines, a survey was carried out and evaluation of the various technologies available within the industry was analysed, including planning tools for RTTR adoption. In addition, a summary of various low-carbon projects was prepared, which demonstrate RTTR technology applications.

4.4.1 Overview of Overhead line Real-time Thermal Rating Technologies

Technologies for the exploitation of overhead line RTTRs can be broadly categorised into (i) sag-based techniques; (ii) tension-based techniques; (iii) conductor temperature-based techniques; and (iv) current rating-based techniques. Each of the techniques, underpinning overhead line RTTR technologies, is described in more detail below:

Sag-based: Technologies that use sag-based techniques monitor the sag of the overhead line conductor either through lasers or radar scans. This may involve the installation of a monitoring unit on the ground in proximity to the overhead line conductor, or on the conductor span itself. Based on the measurement of the overhead line conductor sag the absolute clearance of the overhead can be quantified.

Tension-based: Technologies that use tension-based techniques monitor the tension of the overhead line conductor either through loading cells or strain gauges attached to the conductor surface. Loading cells may be installed at overhead line tension towers on the tower-side of the insulation string. The loading cells or strain gauges tend to be powered by local battery sources that are recharged through solar panels. The monitored tension of the line allows the line sag to be calculated and the absolute clearance of the overhead line to be quantified.

Temperature-based: Technologies that use temperature-based techniques monitor the operating temperature of the overhead line conductor. This can then be directly compared to the maximum operating temperature (design temperature) of the overhead line to ensure statutory clearances are maintained. Retro-fitting temperature sensors to the existing conductor may involve clamping the monitoring equipment to the overhead line or taping a fibre wrap to the exterior of the conductor. In the case of newly-commissioned overhead line infrastructure, a fibre optic cable may be incorporated within the overhead line conductor to provide distributed temperature sensing functionality.

Current rating-based: Technologies that use current rating-based techniques monitor or estimate the environmental conditions (wind speed, wind direction, solar radiation and ambient temperature) in the vicinity of the overhead line. Using environmental conditions monitored in real-time, together with fixed parameters (such as the conductor diameter), the maximum current rating of the overhead line conductor may be calculated that corresponds to the maximum operating (design) temperature. Three widely-used standards for modelling overhead line current limits have been produced by the IEC[1], CIGRE[2] and the IEEE[3].

4.4.2 Overview of RTTR planning tools

In order to plan for the adoption of RTTR technologies it is necessary to:

1. Identify the location of thermally vulnerable components within the power system;
2. Quantify the influence of environmental conditions on power system ratings;
3. Identify equipment suppliers for the various aspects of the RTTR system (such as sensors, telecommunications and control software);
4. Develop an equipment maintenance schedule.

The identification of thermally vulnerable components within the power system may be achieved through (i) offline power system studies (such as the assessment of thermal vulnerability factors[4]); (ii) physical assessment and monitoring of the power system (such as line surveys and Thermo-vision imaging); and (iii) DNO operational experience.

The influence of environmental conditions on power system ratings[5] may be quantified through the development of component thermal models and the population of the models with offline meteorological data relating to the site.

The identification of equipment suppliers and development of maintenance schedules will take place in-line with the DNO's standard practices.

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[1] IEC, 1995, *Standard TR 1597 Overhead electrical conductors – calculation methods for stranded bare conductors*.

[2] CIGRE WG 22.12, 1992, "The thermal behaviour of overhead line conductors", *Electra*, vol. 114 (3), 107-125.

[3] IEEE, 1993, *Standard 738 Standard for calculating the current-temperature relationship of bare overhead line conductors*.

[4] S. C. E. Jupe and P. C. Taylor, 2009, "Distributed generation output control for network power flow management", *IET Proc. Renew. Power Gener.*, vol. 3(4), 371-386.

[5] A. Michiorri, P. C. Taylor, S. C. E. Jupe and C. J. Berry, 2009, "Investigation into the influence of environmental conditions on power system ratings", *Proc. IMechE-Part A: J. Power and Energy*, vol. 223 (A7), 743-757.

4.5 Methodology for the Location of Meteorological Stations

The methodology used to determine the location and number of meteorological stations builds upon the research undertaken by Durham University as part of the 'Active management of distributed generators based on component thermal properties' project. The details regarding the meteorological location specification approach of two other RTTR-related projects are summarised below:

- In Central Networks' (now WPD) RTTR implementation from Boston to Skegness, the 32km 132kV overhead line is instrumented with three conductor temperature sensor locations: one at either end of the line and one at the point of line orientation change, approximately 12.5km from Boston and 19.5km from Skegness.
- In the Northern Ireland Electricity (NIE) RTTR implementation the 100km 110kV line from Omagh to Dungannon is instrumented with 20 sensor locations, situated at regular intervals of 5km along the line.

Clearly a trade-off exists between the investment cost of network instrumentation and the accuracy of data interpolations to achieve adequate network thermal visibility. Therefore, research at Durham University suggests that a maximum distance of 10km between meteorological stations is required for RTTR system-intact operation and to characterise the network thermally, with additional line temperature monitoring to ensure that microclimate regions are covered.

For this project, meteorological stations have been installed at every 132kV substation along the route of the circuits. This approach has the following benefits:

1. The 132kV substations have secure power supplies and reliable private-wired telecommunications networks, which can be made available to the RTTR project;
2. The substation installations offer easy access for DNO personnel, thus aiding equipment maintenance;
3. The meteorological stations are installed on land owned by the DNO and do not require planning permission or consents prior to installation;
4. The substations are secure premises; hence the risk of meteorological station vandalism is reduced.

In areas where the distance between 132kV substations is greater than 10km, alternative locations for the meteorological station installations have been considered. To accomplish this, desktop studies were undertaken to identify possible alternative locations, such as 33kV substations or towers on the 132kV circuits. In addition, GIS and GPRS surveys were carried out to identify potential microclimates and confirm coverage for wireless data transmission respectively. The results of this study are shown in Figure 4-4. The 132kV circuits are shown in blue, the letter 'M' denotes a meteorological station, the blue circles indicate confirmed 132kV substations, the orange circles indicate desirable tower locations on the 132kV overhead line for effective RTTR system operation, and the green circles indicate alternative 33kV substation sites.

The locations indicated by red circles are microclimate regions identified through surveys of the 132kV overhead line terrain and surrounding environment.

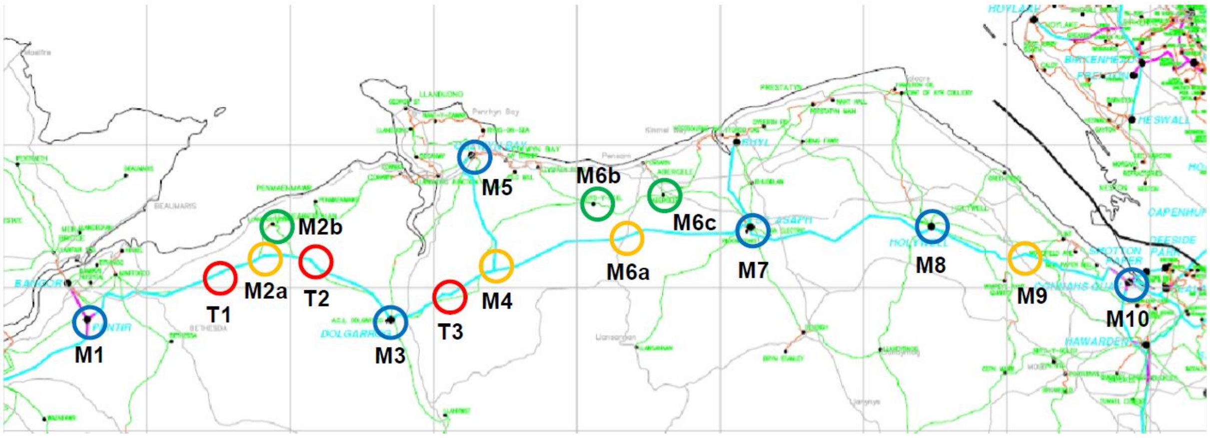

Figure 4-4: Result of a study on the location of meteorological and direct conductor temperature sensing equipment on SP Energy Networks' 132kV network

Further analysis has shown that the installation of meteorological equipment in the 33kV substations was not practical, due to the wind-sheltering effects of the local geography. Furthermore, the private DNO-owned wired telecommunications networks are not available at these substations. It was therefore decided to install the remaining meteorological stations on the 132kV tower locations identified in Figure 4-4 (marked M2a, M4, M6a and M9).

The tower-based meteorological stations are specified to be mounted on the existing 132kV towers at a height near as practicable to just below the lower cross arms. Suitably robust, weather-proof enclosures are affixed to each tower at a height as near as practicable to just above the anti-climb guards, in order to provide termination facilities for the pre-wired meteorological station cables and mounting facilities for the remote terminal unit (RTU) equipment. The meteorological stations and RTUs are powered by batteries, which are charged from solar panels and micro wind turbines. Tower-based communications are via integral GPRS modems located within the RTUs. External antennas are fitted where required. The SIM cards needed to connect to the mobile networks that support GPRS communications are supplied on the basis of network coverage studies. The data from the GPRS transmitters then enters the centralised RTTR module via an ADSL broadband modem.

4.6 Methodology for the Location of Temperature Sensors

The direct conductor temperature monitoring equipment is an additional precaution, and is a tool to assist the control room engineers to gain further confidence in the system. Nine conductor temperature sensors were specified for this system. One could be installed on each circuit within the RTTR implementation project area, and three additional units could be installed in each of the three potential hot-spots identified by red circles in Figure 4-4 (marked T1 to T3).

The conductor temperature sensors are clamped to the conductor jumpers near the towers, and are powered from the electromagnetic fields surrounding the conductors when energised at 132kV. The sensors have a battery back-up facility to enable communication to continue during circuit outages. The signal from the conductor temperature sensors is sent to a tower-mounted base station, which is powered via a battery and solar panel arrangement. Data from the base stations is then relayed to the centralised RTTR module using inbuilt GPRS modems.

4.7 System Architecture

4.7.1 RTTR System Architecture

The architecture of the original field trial system has been modified to make it more repeatable over different areas of the network and more viable for use by control room engineers. To achieve this, the calculation processes have been moved from dispersed locations (monitoring single assets), to a centralised system (monitoring multiple assets) using SP Energy Networks' network management system (NMS). This approach enables the management of the complex system of meshed circuits, through the real-time display of the real-time line rating in the control room environment. The power flows on the RTTR-enabled circuits will be regulated by the constraint of distributed generators and by utilisation of the enhanced thermal state visibility of the power system. A representation of the new RTTR system architecture is given in Figure 4-5.

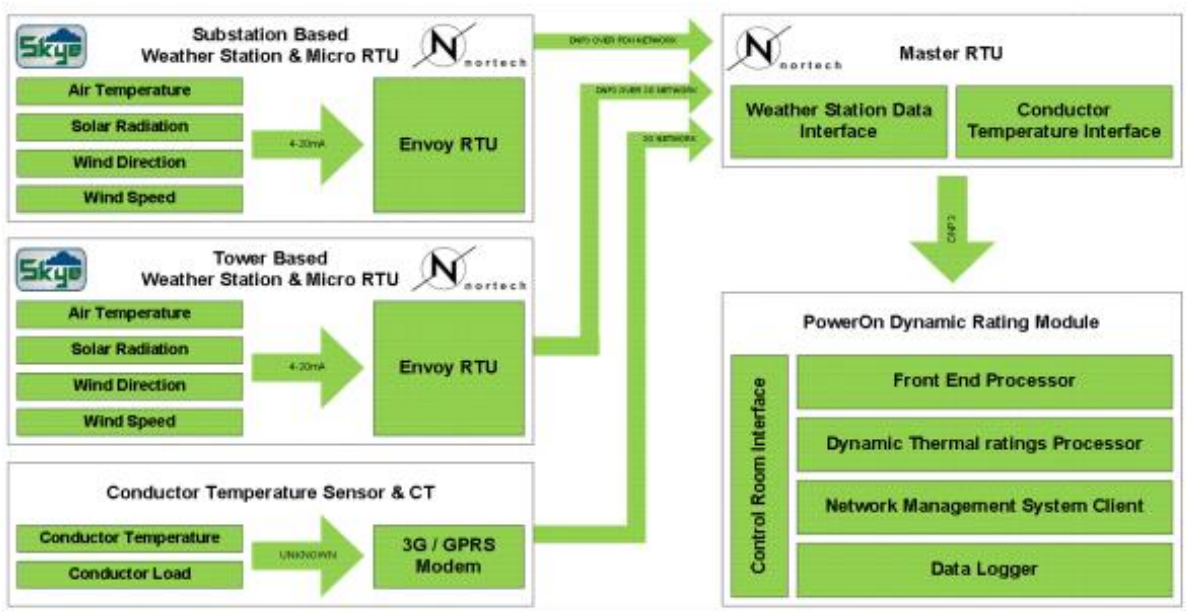

Figure 4-5 RTTR system architecture

4.7.2 System Data

In order to deploy the RTTR system within a section of the electricity network, such as that shown in Figure 4-6, the RTTR algorithms require a number of immediate, non-time varying, parameters to be calculated, based on the following categories of input data:

- Geographical parameters of the overhead lines;
- Electrical and thermal parameters of the overhead lines;
- Meteorological station installation parameters;
- Physical constant parameters;
- User-defined parameters;
- Thermal state estimation parameters.

The functional specification of the RTTR algorithm is given in Appendix C. The data requirements specification for the RTTR system is given in Appendix D. The equipment specifications for weather stations and micro RTUs are given in Appendix E.

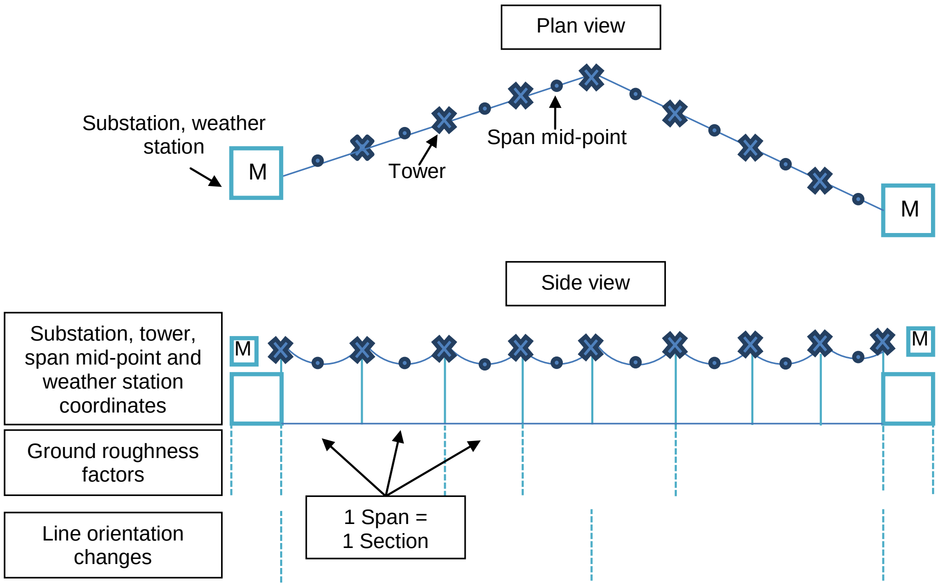

Figure 4-6: Generic representation of the overhead-line system

The majority of data required by the RTTR algorithms is constant, with the only time-varying parameters for the rating calculation being wind speed, wind direction, ambient temperature and solar radiation.

The time-varying data is transmitted to the centralised RTTR module using intelligent RTUs, which have been uniquely specified for this project and are capable of performing complex data manipulation. The use of such RTUs facilitates the remote calculation of TSE values without the requirement to transmit high-resolution meteorological data over the telecommunications networks. This means that information, rather than a data stream, is communicated to the centralised control system and a judicious balance is achieved between distributed and centralised intelligence. In order to achieve this, the RTUs are designed to measure the meteorological data with a sampling rate of 7.5 seconds. At the end of each five-minute time period, that is every forty samples, the RTUs are programmed to calculate maximum, minimum and average values for each meteorological component data set, together with the standard deviation. The above data sets, transmitted at five-minute intervals, are sufficient to facilitate the calculation of both deterministic and probabilistic RTTRs. The probabilistic calculation of RTTRs has been developed for future-proofing the system and is performed using the standard deviation data and Monte Carlo analysis.

The RTUs have also been specified to aid system reliability by enabling the system to detect and manage meteorological sensor errors or telecommunications failures. The data transmitted to the centralised RTTR module includes a health-check signal, which assists with the identification of bad data. When bad, or missing, data is discovered, it is replaced by standard default parameters automatically by the algorithms; the system therefore is able to continue operating following hardware failures, albeit with a degraded RTTR in the affected areas.

To facilitate offline system validation, and to assist with the quality assurance process, key system data is stored in the DNO's data historian.

This data has been chosen as:

- Meteorological data;
- Deterministic RTTR (in Amps);
- Probabilistic RTTR (in Amps);
- Directly monitored conductor temperature data;
- Limiting span;
- Calculated line temperature.

4.7.3 Communications Architecture

The RTTR system communication architecture is given in Figure 4-7. The remote communications consist of two different configurations. The first was used at substations that were already connected to SP Energy Networks' PDH (plesiochronous digital hierarchy) network. This provides a permanently connected circuit between the remote substation and host at St Asaph at 9.6Kbps. PPP (Point-to-Point) protocol was run over this link to provide IP (Internet Protocol) connectivity between the sites.

The second communications setup was used at tower sites and one substation where there was no pre-existing access to the PDH network. This uses GPRS or 3G wireless communications. Each unit was fitted with an O2 SIM card. SIM cards were assigned a static private IP address. An IPSEC VPN link established between the SIM card provider and an ADSL router installed at the substation in St Asaph. This provides a secure end-to-end tunnel between the host at St Asaph and the remote weather station units.

The remote units and the iHost server form a secure network that is separate from SP Energy Networks' corporate and real-time systems networks. As this network is built upon public internet-facing networks, despite best efforts to secure it, there remains a possibility it could be open to attack and compromise. Therefore the link between the iHost server and the PowerOn Fusion server was made DNP3.0 over RS-232 (rather than DNP3.0 over TCP), thus ensuring that IP traffic could not pass from the internet to SP Energy Networks' internal networks.

4.7.4 Software Architecture

The GE solution comprises a PowerOn Fusion™ Distributed Controller Platform (DCP) which interfaces to the Nortech iHost system, provides a display of the output of the RTTR calculations to a web page accessible to the SP Energy Networks control room and feeds weather station input data and calculated rating output data to the SP Energy Networks PI system for further analysis. The software architecture is given in Figure 4-8.

Each of the 132kV circuits being monitored are modelled in PowerOn as a series of line spans with electrical characteristics (e.g. resistance, conductor diameter, absorption coefficient , emissivity coefficient) and physical characteristics (e.g. x & y coordinates, height above ground, ground roughness factor). These are loaded into the PowerOn Dynamic Thermal Rating (RTTR) model via a standalone load tool.

The weather data gathered by the Nortech system and transported over RS232 serial connection, for security purposes, is presented to PowerOn as a series of DNP3 SCADA points. Each weather station input (temperature, wind speed, wind direction and solar radiation) is processed by the PowerOn Front End Processor (FEP) and entered into the PowerOn Real-time (RT) database.

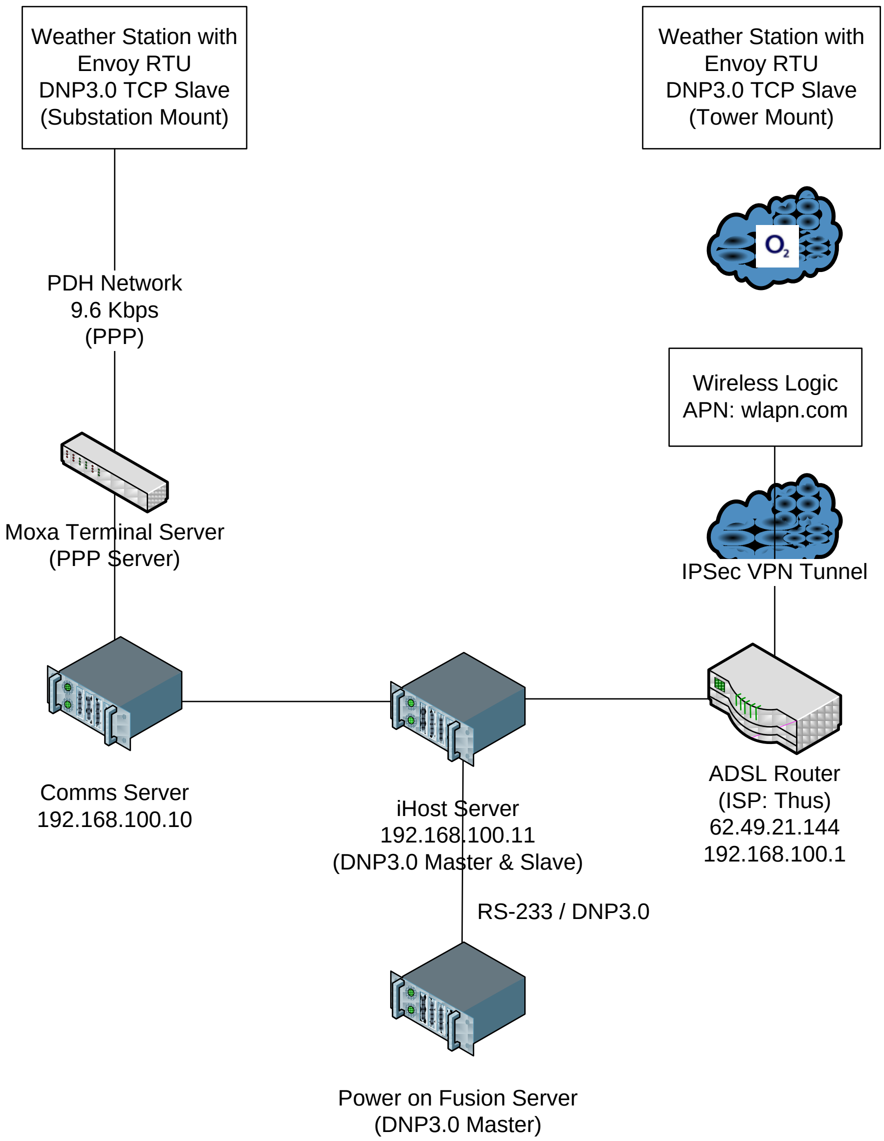

Figure 4-7 RTTR system communications architecture

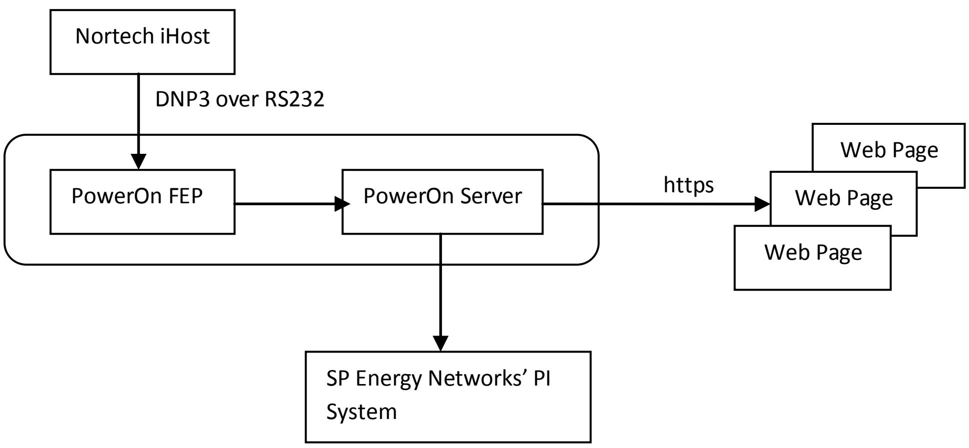

Figure 4-8: RTTR system software architecture

The RTTR process executes every 5 minutes, processing the weather station data against the model for each of the 132kV lines modelled and produces an output of the maximum current in the limiting span of each 132kV line. These values are then represented on a graphical display available to the control room via a live web link to the St Asaph PowerOn client as shown in Figure 4-9.

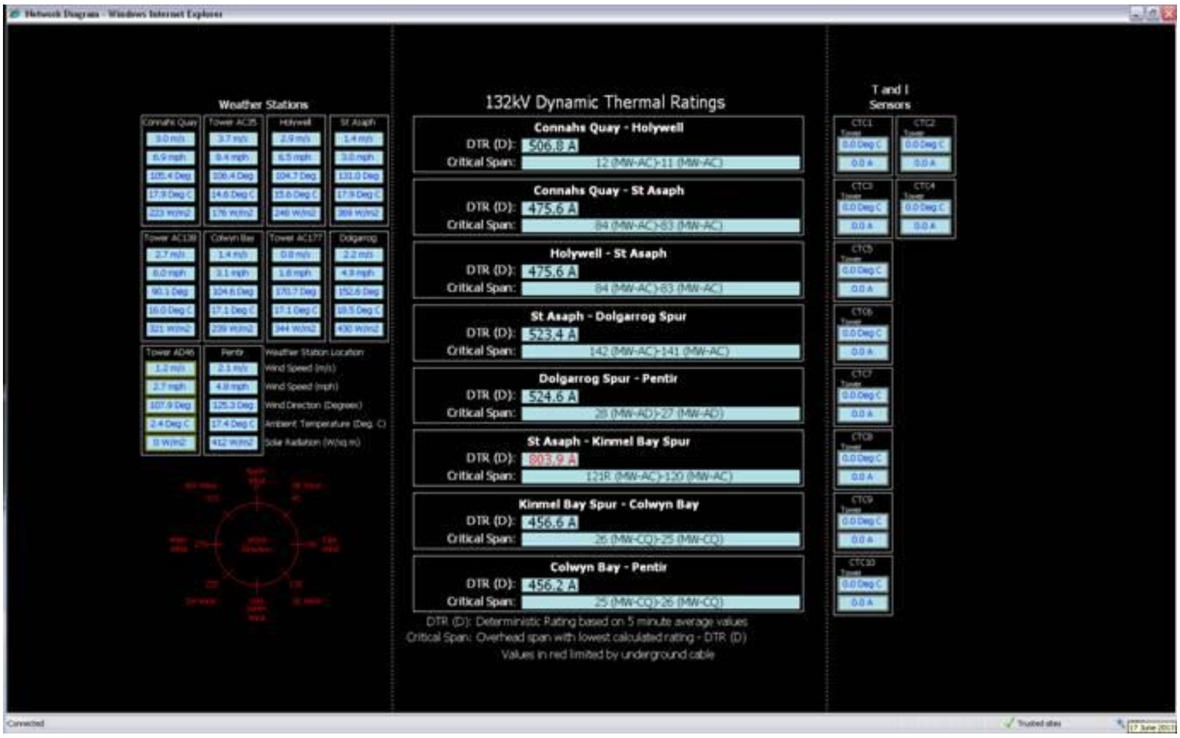

Figure 4-9: The RTTR System Graphical User Interface

Whilst the RTTR scheme was hosted on the stand alone St Asaph client it was agreed that presenting the RTTR in a tabular format would be the most efficient way of conveying the system's performance. The layout highlighted in Figure 4-9 was designed with the following key features:

- Weather Station Data – Live 5 minute average data from the ten weather stations in the left-hand pane, with the stations ordered in terms of the location east – west. The key information presented is:
  - Wind Speed in terms of m/s and mph – the latter being more readily understood and preferred by the control engineers;
  - Wind Direction in degrees with a compass rose for ease of understanding;
  - Ambient Temperature in Degrees Celsius;
  - Solar Radiation in Watts per metre sq;
- RTTR Data – Live 5 minute data for the eight 132kV circuits in the central pane, again order in terms of location east – west. The key information presented:
  - The DTR / RTTR calculated capacity for the circuit in Amps, with the value being the lowest calculated from all of the circuits spans, i.e. the critical span;
  - The name of the critical span, presented in the form extracted from SP Energy Networks' GIS system;

- Temperature and Current Sensor Data – the intention was to present the sensor data in the right hand pane, with each location named as per its tower name and arranged east – west or alongside the circuit(s) it was monitoring;
- Colours / Alarms – where possible the scheme utilised the symbols and analogues that matched the central PowerOn system, with the aim of easing its integration in the future. Coloured borders and fonts were built into the display to highlight when a value becomes stale (i.e. communication issue) or above the static rating of a cable section in the circuit.

Going forward the intention would be to host a similar summary table in the central PowerOn system, with the DTR / RTTR analogue and sensor values duplicated and placed in a suitable location alongside the 132kV line diagram.

As well as the web link, the RTTR data was made available in SP Energy Networks' PI historian, both for viewing in real time and the review / analysis of historic data.

4.8 Equipment Testing Methodologies

4.8.1 Factory Acceptance Tests

The factory acceptance tests comprised a series of structured tests to confirm each sub-module of the GE solution was working correctly, namely: circuit modelling load tool, weather input processing, RTTR algorithm and graphical symbol set. This series of bench tests was undertaken with both a Nortech test system and the actual PowerOn system that was later installed onsite.

Weather Data: As all the weather sensors used on the system are 4->20mA sensors, a calibrated current source was used to simulate each weather input in turn and the reading displayed on the PowerOn symbol was checked to confirm that it matched the expected value. A further set of tests was then undertaken to confirm that the weather lower, upper and standard deviation values being displayed matched those reported by the Nortech Envoy RTUs via the iHost system.

RTTR Algorithm: A specific set of test data was loaded into the system to represent a single circuit with two weather stations on the St Asaph to Holywell circuit. A series of specific weather inputs, representing weather situations such as: bright, hot and still; bright, cool and still; bright, cool and windy; dull, cold and windy were input to the system. The results obtained were then compared to the expected rating provided by Parsons Brinckerhoff from applying the same criteria to their instance of the RTTR algorithm. This successfully showed that the RTTR algorithm was producing the expected result for varying weather conditions.

Symbol Tests: The weather input tests confirmed that the PowerOn symbol was displaying the requisite value for each calibrated input. A further set of tests was undertaken to confirm that the symbol was updated to reflect any bad quality input flagged by the Envoy system.

Data Load: Finally a series of tests were under taken to ensure that the data load tool used to model the electrical/physical attributes of each line span correctly created the requisite PowerOn PFL file and that the file was successfully loaded into a circuit instance.

4.8.2 Site Acceptance Tests

The site acceptance tests of the project comprised a set of structured tests in order to: validate that PowerOn was correctly reading weather inputs for each weather station, the RTTR values produced for each line matched expected values and that the input /output values were being correctly reported to PI (SP Energy Networks' data historian).

Weather station inputs: For each weather station the weather data values shown on the PowerOn symbol for temperature, wind speed, wind direction and solar radiation were validated against the actual value collected by the iHost system.

RTTR values: Each 132kV line section was individually tested by loading just the 132kV line data for that section and the two weather stations for that section. The weather inputs and the output of the RTTR algorithm were then recorded, and the weather inputs were used to drive an IEC model of the same section. The resulting maximum current and limiting span from the IEC model and the RTTR algorithm were then compared.

PI values: Each input and output received by SP Energy Networks' PI system was manually validated against the PowerOn value that was sent to the system.

4.9 Methodologies for the Installation of Equipment

4.9.1 Installation of Substation-based Weather Stations

A Method Statement was developed to outline the procedural methodology to be adopted when installing a weather station in a substation compound, mounted on the side of a substation building. The Method Statement for installation of substation-based weather stations is included for reference in Appendix F. An example substation-based weather monitoring installation is given in Figure 4-10.

4.9.2 Installation of Tower-based Weather Stations

A Method Statement was developed to outline the procedural methodology to be adopted when installing a weather station system on an overhead line tower, powered by a hybrid solar-micro wind turbine-battery system. The weather station system is to be mounted on the lower portion of the overhead line tower, so as to avoid safety clearance infringements. The Method Statement for installation of tower-based weather stations is included for reference in Appendix F. An example tower-based weather monitoring installation is given in Figure 4-11.

Figure 4-10: Substation-based weather station

Figure 4-11: Tower-based weather station

5 The Outcomes of the Project

The following outcomes resulted from this project:

1. Ten weather stations, and the associated information and communication technologies, were successfully installed across 90km of North Wales to implement the real-time thermal rating system;
2. Data from the ten weather station installations was used to calculate the real-time thermal rating of eight circuits for the twelve-month period from 24th September 2012 – 23rd September 2013;
3. The data can be seen on live displays in SP Energy Networks' control room and over web interfaces at locations remote to North Wales, within the UK. In addition, the data is stored within a data historian for offline analysis;
4. For the 12-month period, it was shown that the average uplifts ranged from 1.24 to 1.55 times the static summer rating. The potential average additional annual energy yield ranged from 10% - 44% for the circuits considered.

This section presents the recorded data and results of data analysis from a full year trial of the RTTR system in North Wales, carried out between 24th September 2012 and 23rd September 2013.

The weather parameters, including wind speed, wind direction, ambient temperature and solar radiation, were recorded at ten meteorological stations installed along the 132kV network of North Wales.

The thermal rating for each span of the 132kV circuits in North Wales were calculated using the real-time weather parameters estimated at different points on the network and the physical parameters of each span. The calculated RTTR was compared with the static seasonal thermal ratings, which were applied as follows:

- **Winter:** December, January, February;
- **Autumn/Spring:** September, October, November/March, April;
- **Summer:** May, June, July, August.

5.1 Recorded Weather Parameters

The weather conditions recorded at the ten meteorological stations at thirty-minute intervals over the 12-month period are presented in this section. It should be noted that the RTU measures data and calculates RTTRs every five minutes, however, a resolution of thirty minutes is sufficient for the purposes of this report.

If communication system fails at any point, the same data value is recorded until communications are restored. There was an RTU firmware update from 26th to 30th October 2012 and 3rd to 12th August 2013. The data from these periods has been eliminated in the figures.

Tower AD46 meteorological station is not operational and needed to be decommissioned due to reconductoring the AD overhead line and weak GPRS signal reception. Also, there was a significant delay with the planning permission to install this weather station on an overhead line tower located in the Snowdonia National Park. Therefore, the weather parameters at tower AD46 were recorded but have not provided in this report. The weather data was recorded locally using the adaptive storage functionality of the envoy unit. As a result of this issue, alternative types of telecoms systems with meshed communications networks will be considered for mission-critical operations. In situations where GPRS is the preferred choice of medium for communication, site surveys should be conducted to validate the signal strength. (Signals stronger than -70dBm are recommended).

5.1.1 Wind Speed

Wind speed is highly variable both from meteorological station to meteorological station and over time. Wind speed at a given location is affected by different factors such as height, relief and terrain. Figure 5-1 shows the wind speed variations against time at different meteorological stations in North Wales. The maximum and average wind speeds recorded in the meteorological stations are represented in Table 5-1.

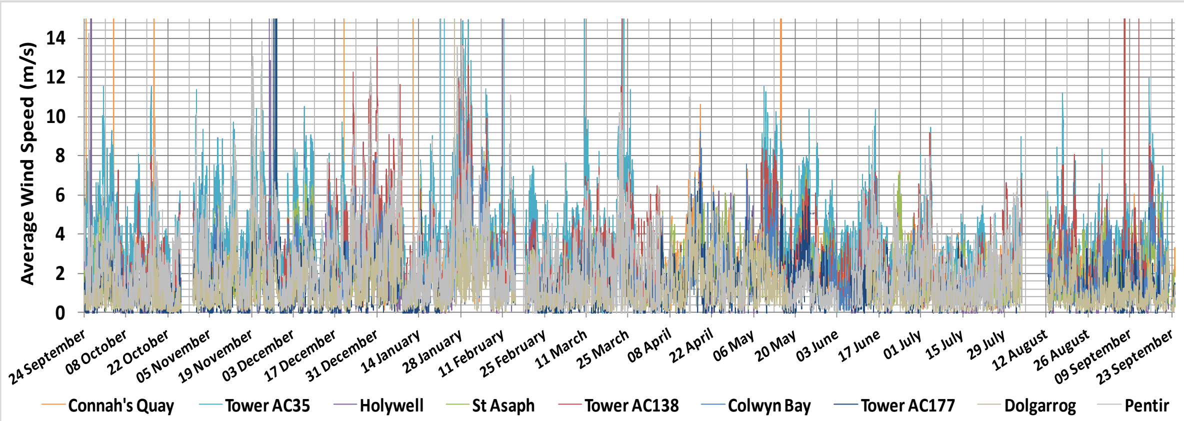

Figure 5-1: Wind speed at the meteorological stations

Table 5-1: The maximum and average wind speed (m/s) across the meteorological stations

Weather station (east-west)	Maximum wind speed (m/s)			Average wind speed (m/s)		
	Summer	Spring/ Autumn	Winter	Summer	Spring/ Autumn	Winter
Connah's Quay	11.4	10.6	8.4	1.9	1.4	1.9
Tower AC35	11.6	16.7	14.9	2.4	2.9	3.5
Holywell	6.8	12.9	8.5	1.0	1.3	1.8
St Asaph	7.4	6.7	8.4	1.5	1.6	2.0
Tower AC138	9.2	13.4	13.7	1.7	1.5	2.6
Colwyn Bay	7.6	9.2	10.3	1.4	1.5	2.0
Tower AC177	6.3	7.1	6.5	0.7	1.2	0.9
Dolgarogg	5.3	9.0	7.0	1.0	1.1	1.4
Pentir	9.3	14.3	13.6	1.1	2.0	2.7

The spike variations at different meteorological stations are due to a malfunction of the ultrasonic wind sensor. The ultrasonic wind sensors have a range of 0 to 60 m/s, so, when the fault occurs, the wind sensors flick between the zero and full-scale values (0 and 60 m/s) which results in average wind speed of 30 m/s. Recent evidence and tests have highlighted that this issue occurs during times of exceptional rainfall. The mitigation of this phenomenon is discussed in Section 9.1.

The overall daily maximum, minimum and average of recorded wind speed in North Wales is reported in Figure 5-2.

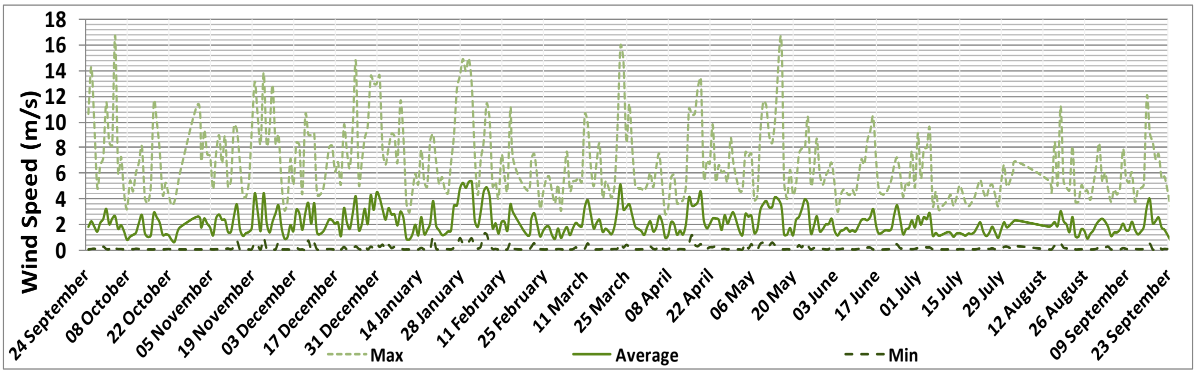

Figure 5-2: Maximum, minimum and average wind speed recorded in North Wales

The highest average wind speed measured along the Connah's Quay-Pentir 132kV network was at tower AC35 at around 16.7 m/s. AC177 is the point with lowest average wind speed (0.7m/s) experienced during a year trial period. (N.B. static overhead ratings assume a wind speed of 0.5 m/s).

5.1.2 Wind Direction

The prevailing wind directions recorded at meteorological stations are shown in Figure 5-3. At most meteorological stations the wind direction is predominantly south-westerly.

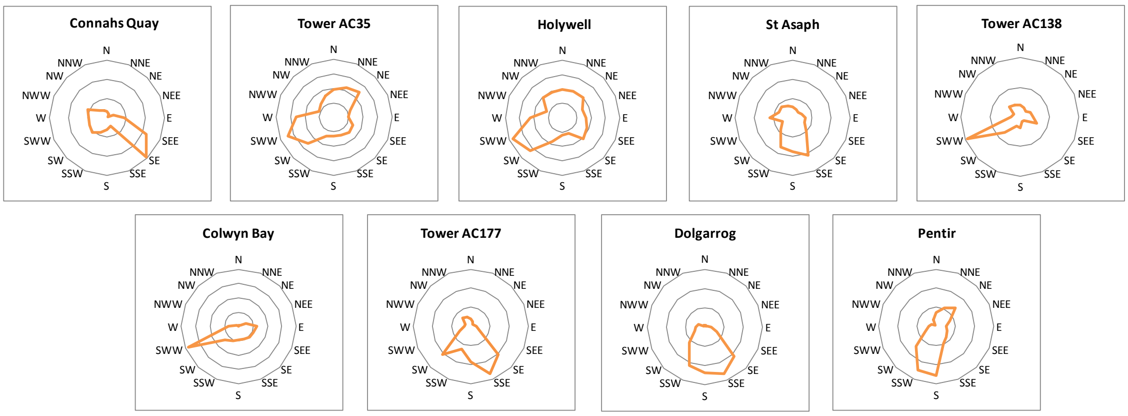

Figure 5-3: Prevailing wind direction at the meteorological stations

5.1.3 Ambient Temperature

The rate of change of ambient temperature is very low compared to that of wind speed. The ambient temperature and its variation are very similar at different locations in North Wales. Figure 5-4 shows the ambient temperature variations recorded at the meteorological stations in North Wales over a year trial period.

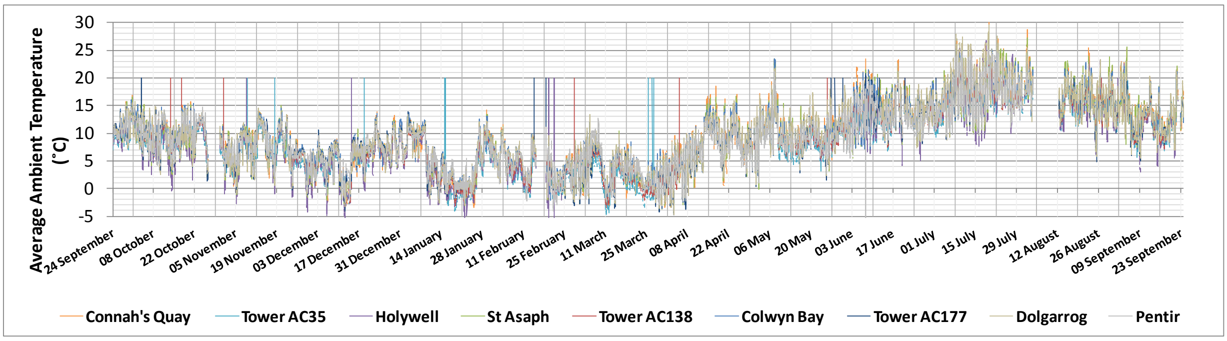

Figure 5-4: Ambient temperature at meteorological stations

The spike-like variations at some of the points at different meteorological stations are due to a malfunction of the temperature sensors. As part of the graceful degradation algorithm, the RTTR system introduces a 20 ˚C default value when the sensor data is judged to have faulted.

Table 5-2 shows the seasonal maximum, minimum and average ambient temperatures at different meteorological stations. The maximum recorded ambient temperature in North Wales was at Connah's Quay (30.3 °C) and the minimum ambient temperature was recorded at Holywell (-6.1 °C).

Table 5-2: The maximum, minimum and average temperatures (°C) across all the meteorological stations

Weather station (east-west)	Maximum temperature (°C)			Minimum temperature (°C)			Average temperature (°C)		
	Summer	Spring/ Autumn	Winter	Summer	Spring/ Autumn	Winter	Summer	Spring/ Autumn	Winter
Connah's Quay	30.3	18.5	14.2	2.7	-3.5	-3.5	15.0	6.8	4.7
Tower AC35	25.4	14.1	12.0	3.2	-4.7	-4.2	12.7	4.6	3.3
Holywell	27.4	14.7	12.6	3.6	-4.2	-6.1	13.8	6.0	4.0
St Asaph	29.0	16.7	13.4	-0.1	-4.0	-3.9	14.5	6.7	5.0
Tower AC138	26.2	13.9	13.7	2.3	-3.5	-3.1	13.3	6.0	4.6
Colwyn Bay	26.8	16.1	13.7	2.3	-3.6	-2.8	14.6	7.1	5.5
Tower AC177	25.2	15.1	13.9	0.3	-4.7	-4.0	12.8	6.6	5.2
Dolgarogg	25.6	15.9	13.4	0.6	-4.7	-3.2	14.7	6.7	5.1
Pentir	25.1	14.9	11.7	1.0	-4.0	-4.0	13.5	6.7	4.9

5.1.4 Solar Radiation

Table 5-3 shows the solar radiation measured at the different meteorological stations in North Wales. The difference between solar radiation recorded at different locations is mainly due to the impact of cloud cover.

The solar radiation variations in a day usually follow a bell-shaped curve. This is demonstrated in Figure 5-4 which shows the solar radiation for a sample day (22nd February 2013) at St Asaph and Pentir.

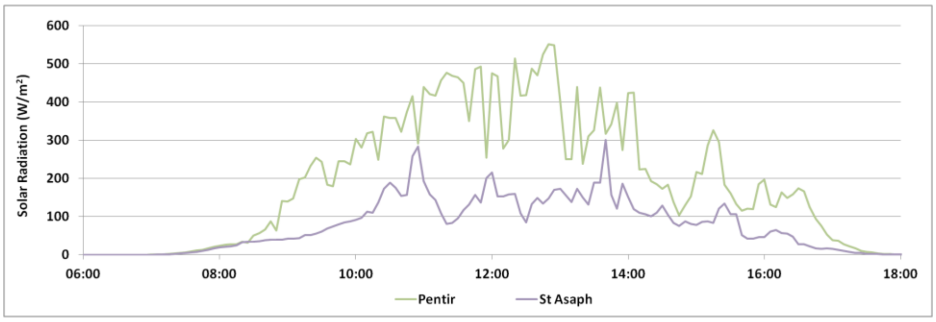

Figure 5-5: Sample of solar radiation variations during 22nd February 2013

Figure 5-6 shows the daily average solar radiation recorded at meteorological stations. It can be observed that solar radiation increases from December to June due to longer daylight time during summer. As Figure 5-6 shows, there is high correlation between average solar radiations recorded at meteorological stations across North Wales.

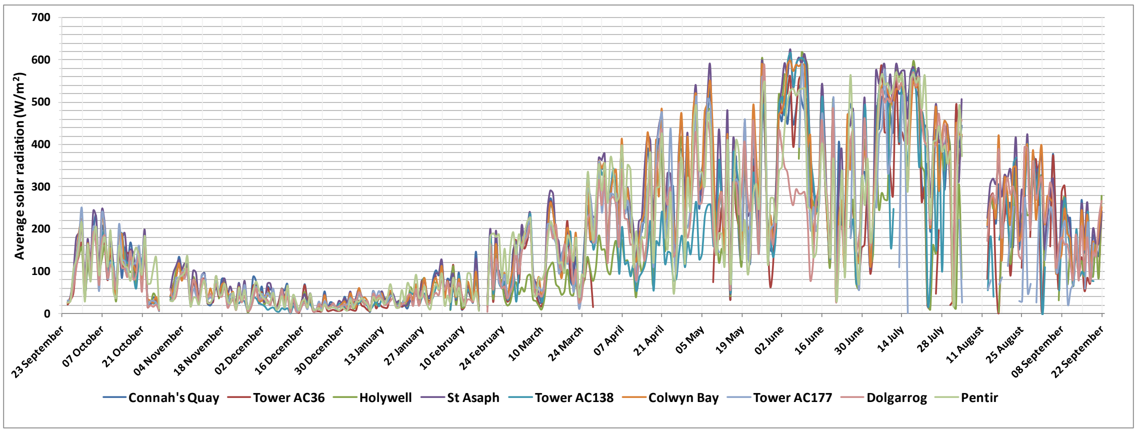

Figure5-6: The daily average solar radiation across the meteorological stations

The seasonal maximum and average solar radiations recorded across North Wales are presented in Table 5-3. The maximum recorded solar radiation was at Colwyn Bay at around 1153.5 W/m^2.

Table 5-3: The maximum and average levels of solar radiation (W/m^2) during daylight hours

Weather station (east-west)	Maximum solar radiation (W/m^2)			Average solar radiation (W/m^2)		
	Summer	Spring/ Autumn	Winter	Summer	Spring/ Autumn	Winter
Connah's Quay	1049.6	872.0	576.7	339.3	156.6	73.4
Tower AC35	959.4	710.8	503.0	287.6	117.1	71.7
Holywell	1058.27	950.2	431.1	307.5	155.6	64.0
St Asaph	1083.0	1014.3	492.5	384.7	177.7	76.6
Tower AC138	992.4	861.0	456.3	310.4	155.2	58.2
Colwyn Bay	1153.5	917.3	479.6	359.5	161.3	70.6
Tower AC177	1054.2	937.9	518.6	268.7	159.1	61.9
Dolgarogg	1060.1	952.5	528.2	325.2	141.1	60.1
Pentir	883.0	819.3	507.6	348.1	159.6	76.5

5.2 Real-time Thermal Ratings of Circuits

This section presents the data analysis of RTTR of the 132kV circuits in the North Wales between Connah's Quay and Pentir. The RTTR system was trialled on eight 132kV circuits. Table 5-4 presents some details about each circuit.

Table 5-4: Details of North Wales 132kV circuits where RTTR is implemented

Circuit	Total Length (km)	Conductor Type	Maximum Altitude* (m)	Minimum Altitude* (m)	Average Altitude* (m)	Arable (%)	Forest (%)	Buildings (%)
Connah's Quay to Holywell	15.7	Lynx	285	14	145	66	30	4
Holywell to St Asaph	13.4	Lynx	252	11	114	56	40	4
Connah's Quay to St Asaph	29.8	Lynx	285	11	129	60	36	4
St Asaph to Kinmel Bay Tee	6.7	Poplar	201	24	110	95	5	0
Kinmel Bay Tee to Colwyn Bay	21.2	19.9km Lynx 1.3km Poplar	310	3	110	59	39	2
Colwyn Bay to Pentir	42.0	6.0km Poplar 36.0km Lynx	420	3	194	43	57	0
St Asaph to Dolgarogg	26.9	7.5km Poplar 19.4km Lynx	308	3	164	68	32	0
Dolgarogg to Pentir	24.0	18.0km Lynx 6.0km Poplar	420	8	219	21	79	0

* Above sea level (0m)

The following section of the report presents the outcomes of RTTR calculations for each circuit. In order to avoid repetition only the detailed analysis of the Connah's Quay - Holywell 132kV circuit is presented. Only key results for the other circuits are included here. The detailed data analysis for these is presented in Appendix G.

5.2.1 Connah's Quay - Holywell

5.2.1.1 Variation of RTTR with Time

Figure 5-7 shows the RTTR calculated for the Connah's Quay-Holywell circuit for a year period. The RTTR of Connah's Quay-Holywell circuit is above the thermal rating the majority of the time (94.3% of time), but there are some occasions when RTTR is below seasonal rating.

5.2.1.2 Variation of RTTR and Load with Time

Figure 5-8 illustrates the loading of Connah's Quay – Holywell circuit against the RTTR. There is no particular correlation between the circuit loading and the RTTR. The maximum Load to RTTR ratio is around 74% which occurs at 19th April 2013 14:00, see Figure 5-9.

5.2.1.3 Thermal Rating Uplift Probability

Figure 5-10 shows the probability of different the thermal rating uplifts. The uplifts are compared with the summer static thermal rating. The horizontal axis refers to the summer rating (389 A, 0% uplift) and the red and blue lines refer to autumn/spring and winter ratings, respectively. The probability of having an RTTR higher than summer rating is around 97.3%.

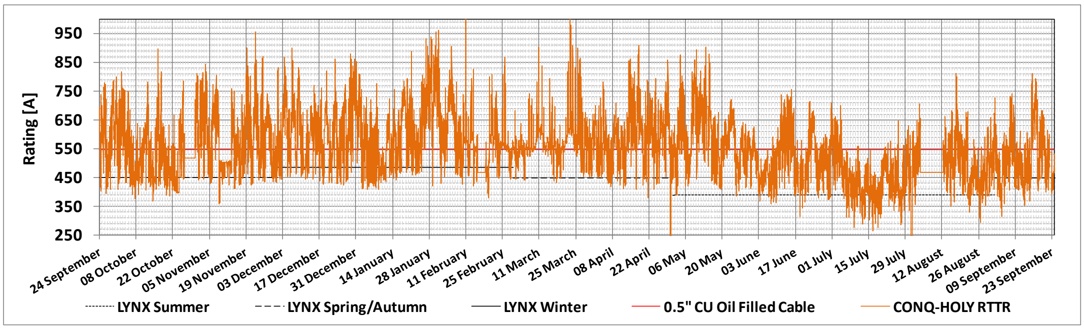

Figure 5-7 - RTTR against time for the Connah's Quay to Holywell circuit

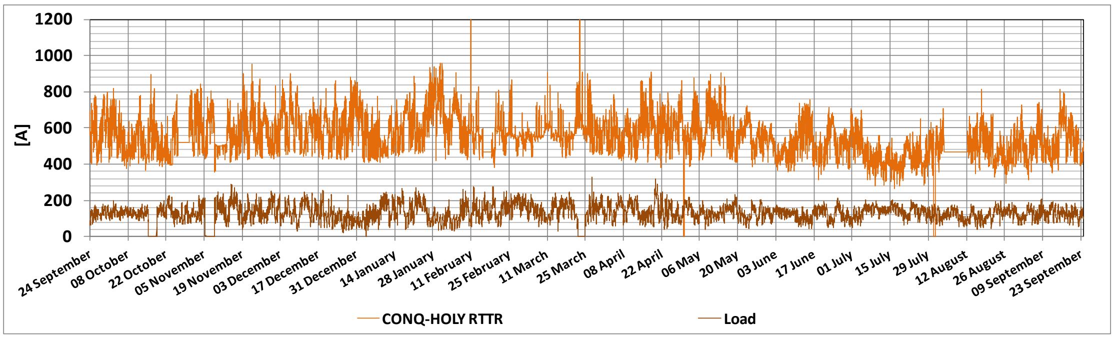

Figure 5-8: RTTR and load against time for the Connah's Quay to Holywell circuit

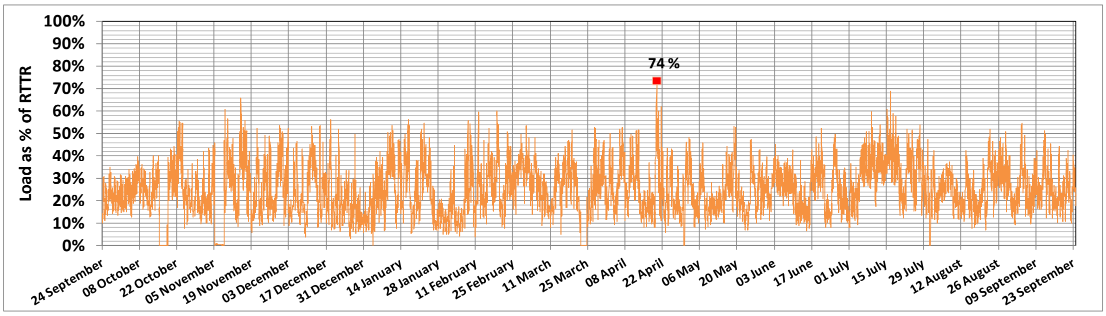

Figure 5-9: Load to RTTR ratio for the Connah's Quay to Holywell circuit

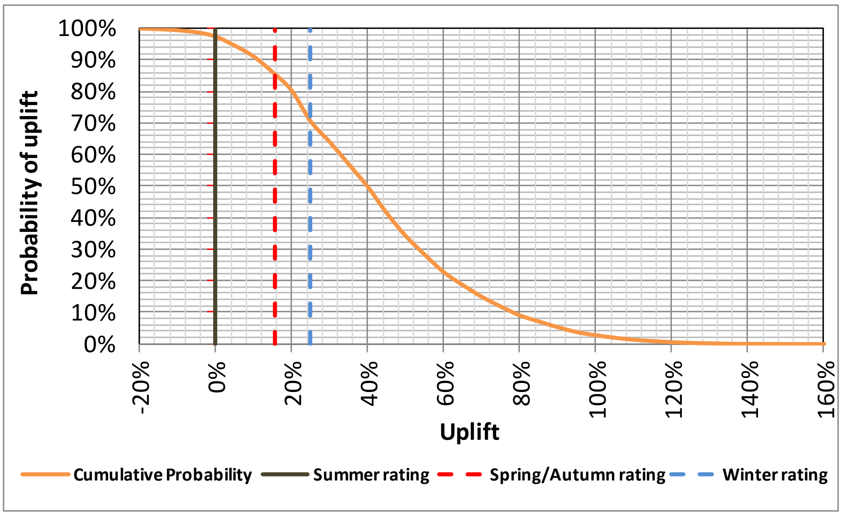

Figure 5-10: The probability of uplift for a twelve month period

5.2.1.4 Energy Yield

Figure 5-11 shows the additional energy which can be transferred through the Connah's Quay – Holywell circuit for different levels of uplift. As an example, with a 30% uplift on the summer rating, an additional 170GWh can be transferred through the Connah's Quay – Holywell circuit. This energy yield is around 73% of the ultimate energy yield, when no constraint is applied on uplift.

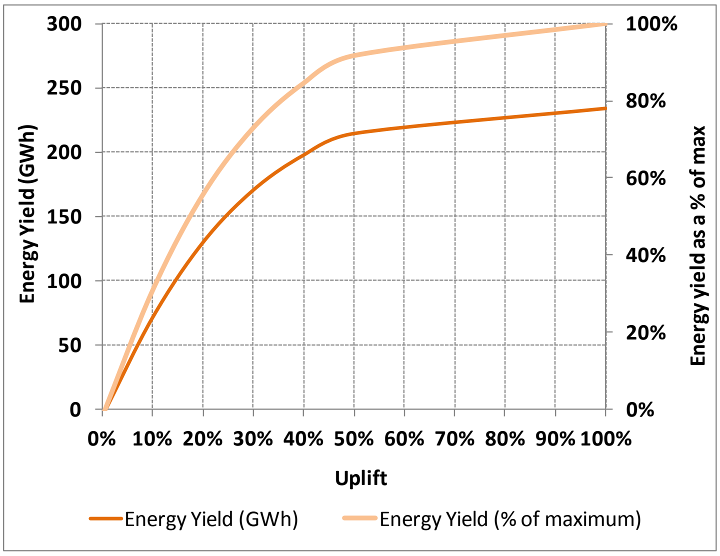

Figure 5-11: The additional energy yield for different uplift levels

5.2.1.5 Critical Spans

Figure 5-12 shows the number of occurrences that each span has been identified as the critical span. The critical span is the span with the lowest RTTR on the circuit, which will be adopted as the RTTR for the entire circuit. AC11-AC12 was identified as the most frequent critical span during the twelve-month trial period. This span is located in a wooded area where the wind speed is reduced due to high ground roughness.

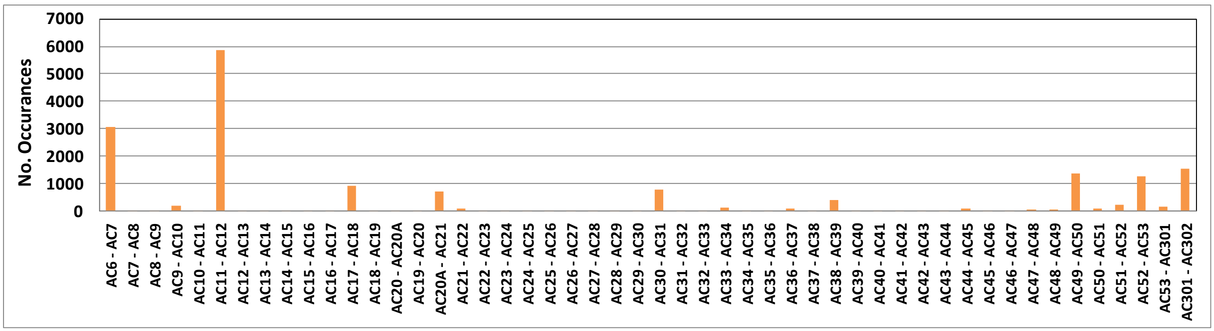

Figure 5-12: The frequency of each span is identified as critical span

5.3 Circuit Highlights

In this section the key results of implementing RTTR system for each circuit are presented. The maximum, average and minimum RTTRs for each circuit for a year trial period are given in Figure 5-13. It was shown that the average uplifts ranged from 1.24 to 1.55 times the static summer rating[6].

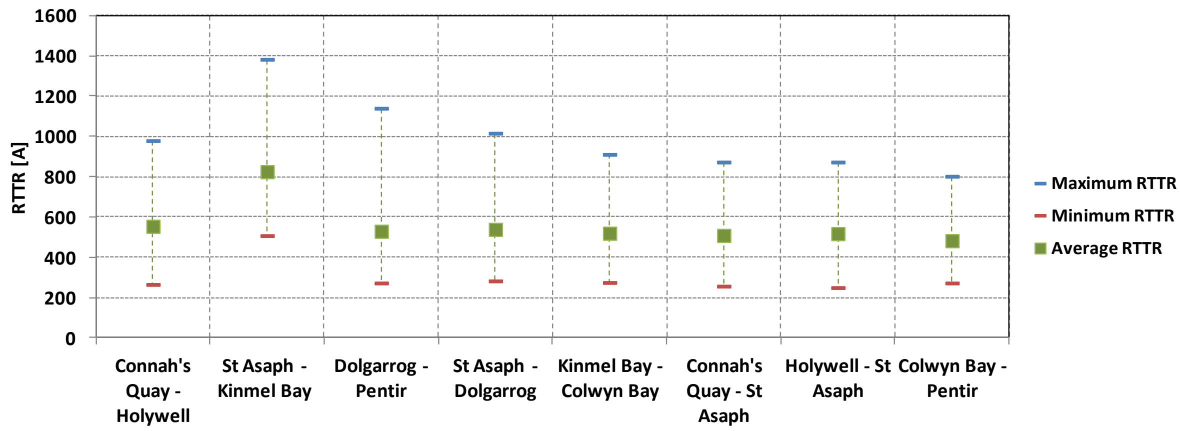

Figure 5-13 Maximum, minimum and average RTTRs for the eight circuits in the trial network

For each circuit a table similar to Table 5-5 highlighting the results is presented.

[6] Based on Figure 5-13 with 389 A and 530 A static summer ratings for Lynx and Poplar conductors respectively

Table 5-5: The key RTTR results highlighted for North Wales circuits

Maximum thermal rating	Maximum thermal rating recorded during the twelve months trial
Average thermal rating	Average of thermal ratings recorded during the twelve months trial
Minimum thermal rating	Minimum of thermal ratings recorded during the twelve months trial
Additional energy yield (summer)	Net additional energy can be transferred through the circuit for different seasons (increased energy minus curtailed energy)
Additional energy yield (Autumn/Spring)	
Additional energy yield (winter)	
Curtailed energy (summer)	The energy below the seasonal rating
Curtailed energy (Autumn/Spring)	
Curtailed energy (winter)	
% of time RTTR above seasonal rating	The percentage of time when the RTTR is higher than seasonal ratings
Maximum Load to RTTR ratio	The maximum ration of Load to RTTR
Most frequent critical span	The most frequent span with the lowest RTTR on the circuit

5.3.1 Connah's Quay to Holywell

Table 5-6: The highlights of the Holywell to Connah's Quay circuit

Maximum thermal rating	979 A @ 10/02/2013 23:30
Average thermal rating	553 A
Minimum thermal rating	264 A @ 16/07/2013 12:30
Additional energy yield (Summer)	80.7 GWh (30.7% of static rating)
Additional energy yield (Autumn/Spring)	96.6 GWh (25.7% of static rating)
Additional energy yield (Winter)	57.1 GWh (23.8 % of static rating)
Curtailed energy (Summer)	1.29 GWh (0.49% of static rating)
Curtailed energy (Autumn/Spring)	2.34 GWh (0.62% of static rating)
Curtailed energy (Winter)	2.11 GWh (0.88% of static rating)
Time RTTR above seasonal rating	94.2 %
Maximum Load to RTTR ratio	74%
Most frequent critical span	AC11-AC12

5.3.2 Holywell - St Asaph

Table 5-7: The highlights of the Holywell to St Asaph circuit

Maximum thermal rating	872 A @ 22/03/2013 02:30
Average thermal rating	517 A
Minimum thermal rating	249 A @ 18/07/2013 14:00
Additional energy yield (Summer)	57.2 GWh (21.8% of static rating)
Additional energy yield (Autumn/Spring)	65.2 GWh (17.4% of static rating)
Additional energy yield (Winter)	43.9 GWh (18.3% of static rating)
Curtailed energy (Summer)	2.32 GWh (0.88% of static rating)
Curtailed energy (Autumn/Spring)	4.70 GWh (1.25% of static rating)
Curtailed energy (Winter)	2.74 GWh (1.14% of static rating)
% of time RTTR above seasonal rating	90.4%
Maximum Load to RTTR ratio	61%
Most frequent critical span	AC94-AC95

5.3.3 Connah's Quay - St Asaph

Table 5-8: The highlights of the Connah's Quay- St Asaph circuit

Maximum thermal rating	872 A @ 22/03/2013 02:30
Average thermal rating	508 A
Minimum thermal rating	256 A @ 18/07/2013 14:30
Additional energy yield (Summer)	53.2 GWh (20.2% of static rating)
Additional energy yield (Autumn/Spring)	56.6 GWh (15.1% of static rating)
Additional energy yield (Winter)	39.7 GWh (16.5 % of static rating)
Curtailed energy (Summer)	2.48 GWh (0.94% of static rating)
Curtailed energy (Autumn/Spring)	5.02 GWh (1.34% of static rating)
Curtailed energy (Winter)	3.16 GWh (1.32% of static rating)
% of time RTTR above seasonal rating	89.7%
Maximum Load to RTTR ratio	57%
Most frequent critical span	AC94-AC95

5.3.4 St Asaph - Kinmel Bay Tee

Table 5-9: The highlights of the St Asaph-Kinmel Bay Tee circuit

Maximum thermal rating	1382 @ 05/02/2013 23:30
Average thermal rating	824 A
Minimum thermal rating	507@ 04/09/2013 15:00
Additional energy yield (Summer)	150.5 GWh (41.8% of static rating)
Additional energy yield (Autumn/Spring)	207.7 GWh (42.8% of static rating)
Additional energy yield (Winter)	145.4 GWh (48.4% of static rating)
Curtailed energy (Summer)	0.00 GWh (0.0% of static rating)
Curtailed energy (Autumn/Spring)	0.00 GWh (0.0% of static rating)
Curtailed energy (Winter)	0.70 GWh (0.0% of static rating)
% of time RTTR above seasonal rating	99.9%
Maximum Load to RTTR ratio	56%
Most frequent critical span	AC103A-AC104R

5.3.5 Kinmel Bay Tee - Colwyn Bay

Table 5-10: The highlights of the Kinmel Bay Tee – Colwyn Bay circuit

Maximum thermal rating	910 @ 05/02/2013 13:30
Average thermal rating	518 A
Minimum thermal rating	274 @ 19/07/2013 12:00
Additional energy yield (Summer)	58.6 GWh (22.3% of static rating)
Additional energy yield (Autumn/Spring)	64.2 GWh (17.1% of static rating)
Additional energy yield (Winter)	45.6 GWh (19.0% of static rating)
Curtailed energy (Summer)	1.93 GWh (0.74% of static rating)
Curtailed energy (Autumn/Spring)	3.89 GWh (1.04% of static rating)
Curtailed energy (Winter)	2.58 GWh (1.08% of static rating)
% of time RTTR above seasonal rating	91.4%
Maximum Load to RTTR ratio	94.0%
Most frequent critical span	CQ25-CQ26

5.3.6 Colwyn Bay - Pentir

Table 5-11: The highlights of the Colwyn Bay - Pentir circuit

Maximum thermal rating	801 @ 30/01/2013 15:30
Average thermal rating	481 A
Minimum thermal rating	261 @ 07/05/2013 14:00
Additional energy yield (Summer)	35.6 GWh (13.5% of static rating)
Additional energy yield	39.2 GWh (10.4% of static rating)
Additional energy yield (Winter)	29.4 GWh (12.3% of static rating)
Curtailed energy (Summer)	4.02 GWh (1.53% of static rating)
Curtailed energy (Autumn/Spring)	8.50 GWh (2.26% of static rating)
Curtailed energy (Winter)	4.88 GWh (2.03% of static rating)
% of time RTTR above seasonal rating	84.1%
Maximum Load to RTTR ratio	86%
Most frequent critical span	CQ25-CQ26

5.3.7 St Asaph - Dolgarogg

Table 5-12: The highlights of the St Asaph-Dolgarogg circuit

Maximum thermal rating	1015 @ 22/03/2013 09:30
Average thermal rating	538 A
Minimum thermal rating	282 @ 26/08/2013 12:00
Additional energy yield (Summer)	67.3 GWh (25.6% of static rating)
Additional energy yield (Autumn/Spring)	82.9 GWh (22.1% of static rating)
Additional energy yield (Winter)	59.0 GWh (24.6% of static rating)
Curtailed energy (Summer)	1.74 GWh (0.66% of static rating)
Curtailed energy (Autumn/Spring)	5.66 GWh(1.51% of static rating)
Curtailed energy (Winter)	3.48 GWh (1.45% of static rating)
% of time RTTR above seasonal rating	89.4%
Maximum Load to RTTR ratio	69%
Most frequent critical span	AC145-AC146

5.3.8 Dolgarogg - Pentir

Table 5-13: The highlights of the Dolgarogg-Pentir circuit

Maximum thermal rating	1139 @ 25/01/2013 21:00
Average thermal rating	528 A
Minimum thermal rating	261 @ 16/07/2013 13:30
Additional energy yield (Summer)	54.5 GWh (20.7% of static rating)
Additional energy yield (Autumn/Spring)	78.2 GWh (20.8% of static rating)
Additional energy yield (Winter)	56.3 GWh (23.5% of static rating)
Curtailed energy (Summer)	2.82 GWh (1.07% of static rating)
Curtailed energy (Autumn/Spring)	4.48 GWh (1.19% of static rating)
Curtailed energy (Winter)	2.06 GWh (0.86% of static rating)
% of time RTTR above seasonal rating	91.2%
Maximum Load to RTTR ratio	84%
Most frequent critical span	AD2-AD3

5.4 RTTR and wind power correlation

Data analysis demonstrated that there is a high correlation between the wind farms outputs and RTTRs of the overhead lines. The recorded output of a local wind farm which is connected to St Asaph substation with an output rating of 21.25MW is compared with the thermal rating uplifts of the North Wales overhead lines.

Figure 5-14 and Figure 5-15 show the probability of different uplifts against different output levels of wind farm recorded in summer and winter. These figures demonstrate that when wind power generation increases, due to faster wind speeds, the RTTR will also increase. This could allow a higher level of integration of wind power into the system without the need for network reinforcement.

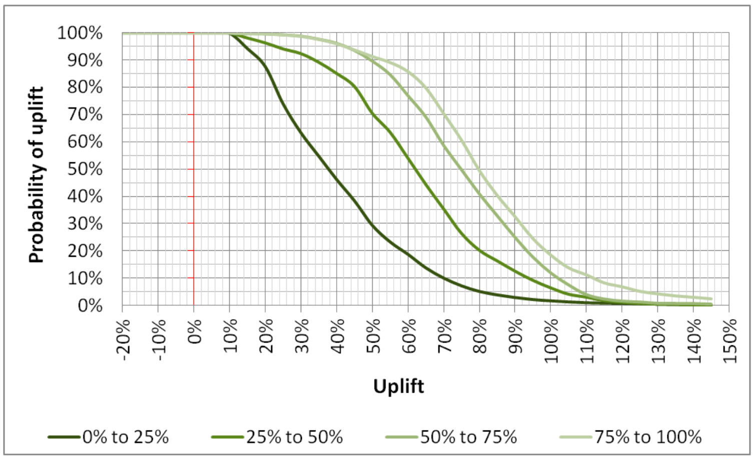

Figure 5-14: The probability of real time thermal rating uplift for different levels of wind power output – winter period

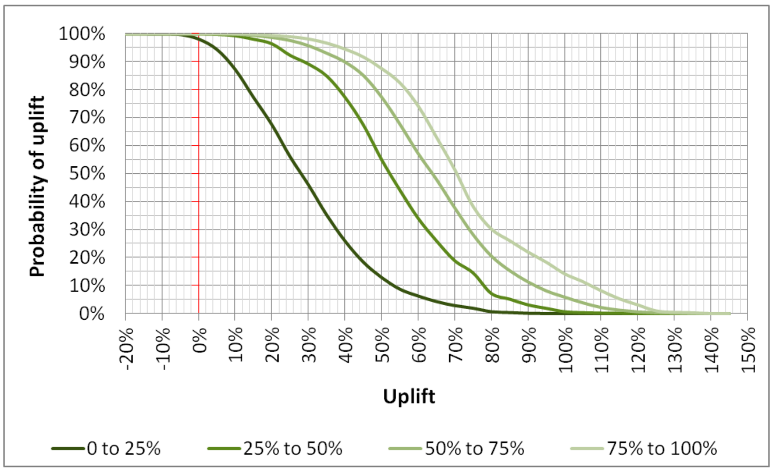

Figure 5-15: The probability of real time thermal rating uplift for different levels of wind power output – summer period

A summary of a year of operational data is given in Appendix G. Detailed analysis of this data is given in Appendix H for the quarter four (Q4) period of 2012 from October to December. Raw datasets (weather parameters and circuit RTTR profiles) have been included in Appendix I.

5.5 Technology Readiness Level

Based on the trials of the Method within this project, the Technology Readiness Level (TRL) of this type of RTTR system has increased from TRL 5 (Technology component and/or basic technology subsystem validation in a relevant environment) to TRL 7 (Technology system prototype demonstration in an operational environment).

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

The project succeeded in delivering all the intended outputs to fulfil the original project objectives. The project performance was evaluated against its original success criteria. Criteria 1, 3, 4 and 5 were achieved within the project lifetime, Criterion 2 was achieved by October 2013 (within 3 months of submission of the initial Close Down Report).

6.1 Project Performance Relative to its Aims and Objectives

The project succeeded in delivering all the intended outputs to fulfil the original project objectives. This section evaluates the project performance against its original aims and objectives.

Renewable generation is often connected in rural locations where there is limited spare capacity within distribution networks. This project aimed to unlock extra capacity in the networks, thus reducing reinforcement requirements and connection costs for wind generators.

This project has demonstrated the potential capacity that can be unlocked within eight circuits of a 132kV distribution network, through the practical implementation of an RTTR system. The uplifts from the system have been quantified and compared to the base-case of static seasonal operating ratings and network reinforcement to unlock similar capacities. The indicative costs of the RTTR system deployment have been quantified and compared to network reinforcement indicative costs. The lower upfront costs, lower maintenance costs and the potential for rapid deployment of the RTTR system make this an attractive option for generators (particularly wind farms) when compared to network reinforcement.

The scope of this project was to implement a real-time thermal rating system for overhead lines that gives the control room operators greater visibility of the actual thermal operating status of their network.

Prior to this project, SP Energy Networks had limited real-time visibility of the thermal status of the distribution network. This project has delivered an RTTR system that provides SP Energy Networks' control engineers with enhanced thermal visibility of the 132kV network between Connah's Quay and Pentir. The RTTR of each overhead line span within this network is calculated and the span with the lowest rating is selected to represent the rating of the entire circuit.

The implementation involved the installation of meteorological stations, the data from which was processed to display RTTRs on a graphical user interface within the distribution network control room. Moreover, functionality was designed into this system to allow the data from conductor monitoring equipment installations to be displayed, in real-time, on the graphical user interface. This could provide system operators with additional information for confidence during the early stages of RTTR system adoption.

The site acceptance testing of the system took place from 23rd – 26th April 2012 and the system began reporting back RTTR information to the server in St Asaph during early May 2012.

The objective was to deliver the first active distribution network-based implementation of this technology across a wide area of the network.

The prototype RTTR system, developed in the fore-running project (Active Management of Distributed Generators Based on Component Thermal Properties), was deployed on a 7km section of 132kV distribution network. This project delivered a system that calculated RTTRs for eight circuits within the 90km area from Connah's Quay to Pentir.

Through open-loop analysis of the real-time thermal rating system, and confidence-building in the technology adoption, the system will then feed into an 'Active Network Management' project, which will facilitate and manage the connection of the wind farms on congested networks.

A Business Adoption Strategy was developed as part of the RTTR system trial and is soon to be implemented by SP Energy Networks. Furthermore, SP Energy Networks are planning a follow-on project, focused on ANM in readiness for the accommodation of prospective wind generation connection applications.

6.2 Project Performance Relative to its Success Criteria

This section evaluates the project performance against its original success criteria, as described in the Project Registration Pro-forma.

Install the necessary equipment to support an open-loop control system infrastructure to facilitate the connection of embedded generation.

This criterion was almost completely fulfilled. The following equipment was successfully installed as part of the RTTR control system infrastructure:

1. Ten weather station nodes (six substation-mounted and four tower-mounted units);
2. Ten RTUs for data communication;
3. RTU master;
4. RTTR server;
5. Communications systems for data transfer within SP Energy Networks.

The RTTR system would have benefited from the installation of conductor temperature monitoring equipment to provide further validation of the RTTR system behaviour. However, due to supply chain issues and outage constraints, this element of the project did not take place.

Prove the integrity of the real-time thermal rating technology embedded within PowerOn Fusion Network Management System (NMS) through data analysis of one-year's operation as a minimum.

This criterion was completely fulfilled by October 2013. Four quarterly reports were generated, using data analysis techniques to demonstrate the integrity of the RTTR system embedded within the PowerOn Fusion Network Management System. RTTR system Quarterly Reports are available on SP Energy Networks' website for the periods (Q4 2012, Q1 2013, Q2 2013 and Q3 2013).

The reports encompass the following elements:

1. A summary of weather conditions;
2. Graphs of RTTR variation with time;
3. Graphs of RTTR and load variation with time;
4. Graphs of the RTTR to loading ratio;
5. Graphs of potential energy yields / power transfers;
6. Graphs of the cumulative probability of RTTR uplift;
7. Graphs of the correlation of RTTR uplift with wind farm output;
8. Graphs of critical span frequency.

Build the confidence of SP Energy Networks to adopt the technology.

This criterion has been completely achieved, recognising that RTTR systems should be deployed with ANM control systems to utilise capacity gains and control power flows at times of high generation and low thermal ratings. A Business Adoption Strategy was developed as part of the RTTR system trial and is soon to be implemented.

Ensure that network integrity and security of supply are not compromised during all stages of the project.

This criterion was completely fulfilled. Network integrity and security of supply were not compromised at any stage during the project.

Provide accurate documentation to facilitate change control through the course of the project (e.g. changes in staff working on project).

Accurate project documentation was maintained by Parsons Brinckerhoff on behalf of SP Energy Networks throughout the project. The following elements of the project were managed on a regular basis by SP Energy Networks with support from Parsons Brinckerhoff:

1. Project definition (including the project brief, Project Registration Pro-forma and summary of parties involved in the project);
2. Scope definition (including conditions of contract, budgets, project durations, scope of work, deliverables, and commercial, legal and programme risks);
3. Project programme (developed using the Microsoft Project Gantt Chart tool);
4. Project resource (summarising the names, roles and responsibilities of parties involved in the project);
5. Work breakdown structure;
6. Project documentation review plan (summarising the project's quality management strategy);
7. Communications and meetings (maintaining accurate and up-to-date records of all internal and external project communications, maintenance of contact lists);
8. Project controls (including filing and document controls, cost controls, change controls, risk management and design management).

The following project folder structure was used throughout the project to facilitate change control:

1. Project management;
2. Meeting Minutes, Agendas & Presentations;
3. Technical;
4. NMS Integration;
5. Communications & SCADA;
6. Weather stations;
7. Validation Equipment;
8. Site data & Installation;
9. Sag Monitors;
10. Communications (Outlook);
11. Dissemination.

A smooth transition took place between Parsons Brinckerhoff project managers during November 2011.

The project and project management process was independently audited by DNV in October 2012, which maintained Parsons Brinckerhoff's ISO 9001, 14001 and 18001 accreditation.

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

The following modifications were required during the course of the project:

1. Increased number of weather stations;
2. Development of tower-based weather station units;
3. Tower-based weather station design;
4. Weather station installation methodology;
5. Modifications to algorithm inputs;
6. Evolution to the deployment of a graceful degradation algorithm.

7.1 Increased Number of Weather Stations

Six substation-based weather stations were included in the original project budget. This number was increased to ten to provide redundancy in case of equipment failure, outages for maintenance / telecoms interruptions.

7.2 Development of Tower-based Weather Stations

In addition to substation-based weather stations, tower-mounted weather station units were developed to provide coverage in remote locations. This provided redundancy in case of equipment failure, outages for maintenance / telecoms interruptions. The tower-based weather stations also provided increased thermal visibility and their proximity to the overhead line conductors provided an accurate representation of prevailing meteorological conditions local to the overhead line itself.

7.3 Tower-based Weather Station Design

The design of tower-based weather station units was modified following an initial installation trial on an overhead line training tower. During the initial trial installation, it was identified that the battery weight needed to be reduced for ease of handling and installation. The tower-based weather station design makes use of correlations between the electrical current to power the instrumentation and the electrical current supplied by the micro wind turbine, solar panels and battery system. For example, at high wind speeds the anemometer (wind speed and direction sensor) draws the largest amount of electrical current and this is also when the micro wind turbine supplies a large amount of electrical current to the monitoring system. Similarly, in bright sunny conditions with high solar radiation, the pyrometer (light sensor) draws the largest amount of current and this is also when the solar panels are supplying a large amount of electrical current to the monitoring system. These correlations, together with reductions in the current drawn by the micro RTU, allowed the battery weight to be reduced from 50kg to 15kg without significantly reducing the level of redundancy provided by the battery system for potential extended periods of low solar radiation and minimal wind speeds.

7.4 Weather Station Installation Methodology

The weather station installation methodology was modified to allow the small wiring of the weather station and RTU to be completed on the ground, designing out the need for working at height for extended periods of time. This reduced the time taken to complete the small wiring operations. In addition, wiring diagrams were included as standard in each RTU cabinet and junction box for future reference and ease of maintenance.

7.5 Input Data Corrections

The system was initially deployed with a 5°C correction factor applied to reduce the maximum operating temperatures of conductors. However, this correction factor was removed as it was felt to give unnecessarily pessimistic rating values. The RTTR system can be configured to take into account a range of conductor types and maximum operating temperatures within the same circuit.

However, for the purposes of this trial, instrumentation tolerances were taken into account and the worst case tolerance condition was used for each monitored parameter.

7.6 Graceful Degradation

A graceful degradation algorithm was deployed within the RTTR system whereby increasingly conservative estimates of the RTTR of conductors were calculated as an increasing number of communication signals were lost. Initially, the algorithm replaced missing or erroneous signals with standard default parameters (0.5m/s wind speed, 12.5° wind incident to the conductor, 20°C ambient temperature and 0W/m^2 solar radiation). However, switching to default conditions was felt to be too conservative and led to unnecessarily pessimistic RTTRs.

The development of graceful degradation algorithms will be planned into the scope of follow-on projects, using a combination of last known values, weather data interpolation and historical datasets, as illustrated in Figure 7-1. In this figure, wind sensors are installed in the system at 0km (A), 12km (B) and 20km (C) from the datum point. The blue curve illustrates the variation in wind speed across the system with all three weather stations intact and functioning. (The wind speeds for system intact operation are 4m/s, 3m/s and 6m/s for the 0km, 12km and 20km weather stations respectively). In this system, weather station (B) experiences a fault and is removed from the RTTR calculation. The red and green curves represent a conservative estimation of the wind speed at node location (B) after 15 minutes and 30 minutes respectively.

7.7 Conductor temperature sensors

The RTTR system would have benefited from the installation of conductor temperature monitoring equipment to provide further validation of the RTTR system behaviour. However, due to supply chain issues and outage constraints, this element of the project did not take place. This impacted on the eventual Technology Readiness Level (TRL) of the RTTR system and, at project close down, the system was assessed to be TRL 7 (Technology system prototype demonstration in an operational environment) rather than TRL 8 (Actual technology system completed and qualified through test and demonstration). During the course of the project new technologies for RTTR system deployments have emerged. SP Energy Networks has plans to trial a subset of these technologies.

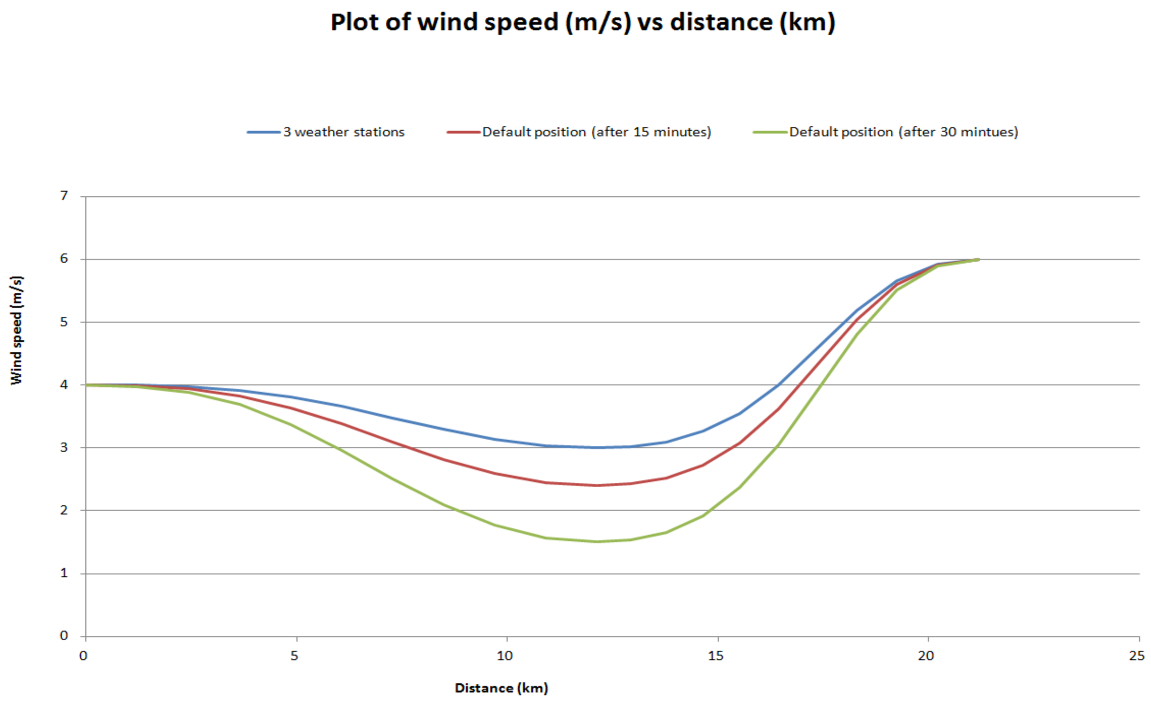

Figure 7-1 Graceful degradation example

8 Significant Variance in Expected Costs and Benefits

Variance in costs

The original project cost was £450,000, whereas, the actual project cost £620,000 (+37%). The Project Registration Pro-forma was re-submitted in 2013 and the project was delivered within the revised budget. The additional £170,000 in project costs was necessary expenditure and arose from:

1. The variation in contracts for weather stations and access equipment (£37,000), due to an increased number of weather stations required for system deployment to provide a sufficiently confident level of thermal visibility of the network;
2. The costs that were required to develop IT systems that were compliant with SP Energy Networks' existing policies (£80,000);
3. Additional SP Energy Networks labour (£51,000) due to increased requirements for field staff to deploy the weather stations and IT equipment.

Variance in benefits

- The previous research and development (R&D) project reported the range of theoretical average uplifts that could be achieved through deployment of overhead line real-time thermal rating systems as 1.70 to 2.53 times the static summer rating. Furthermore, it was reported that the additional annual energy yield from distributed generation that could potentially be accommodated through deployment of an RTTR was found to be 20 – 54% for the cases considered;
- This LCNF project has built on the R&D project to establish the practical exploitable headroom that could be unlocked through a wide-scale deployment of RTTR systems. In this case, it was found that the average uplifts ranged from 1.24 to 1.55 times the static summer rating. The potential average additional annual energy yield ranged from 10% to 44% for the circuits considered.

8.1 Variance in Costs

Table 8-1 highlights the variation between SP Energy Networks' planned expenditure at the start of the project (July 2010), when the expenditure was reforecast and the actual expenditure at the project's close down in July 2013.

Table 8-1 Variance in Project Costs

Element	Forecasted Expenditure (July 2010)	Reforecast Expenditure (May 2013)	Actual Expenditure (July 2013)	Variance (from July 2010)	Variance
Contracts	£210,000	£250,000	£246,846	£36,846	+17.5%
IT	£195,000	£270,000	£272,952	£77,952	+40%
Labour	£45,000	£95,500	£95,695	£50,695	+112%
Materials	-	£1,306	£1,306	£1,306.28	N/A
Legal	-	£3,200	£3,200	£3,200	N/A
TOTAL	**£450,000**	**£620,000**	**£620,000**	**£170,000**	**+37%**

8.1.1 Contracts

The £36,846 (+17.5%) variance in the forecasted and actual expenditure under Contracts was a result of the following elements:

8.1.1.1 Engineering Consultants

This was the largest contract placed in the project as such to control expenditure a framework agreement was established between SP Energy Networks and Parsons Brinckerhoff for the duration of the project. This approach enabled both parties to ensure the project expenditure was in line with the initial forecast with only a marginal over expenditure (+5.45%).

8.1.1.2 Weather Stations

As detailed in Section 7 the project's initial approach required the installation of six weather stations at the Grid Substations along the 90km stretch of the 132kV network. However, early in the project it was decided that a weather station separation of no more than 10km was required to ensure the TSE approaches performance and to provide the RTTR scheme with redundancy. To achieve this, an additional four GPRS-based micro RTUs and weather stations had to be procured. Furthermore each of these additional units had to be modified to enable them to be self powered and mounted on 132kV steel towers. This required the design, selection and procurement of tower brackets, batteries, micro wind turbines and PV panels for each of the additional stations. As a result, the cost of each of the additional weather station sites was approximately three times more expensive as the substation based units. NB – This additional expenditure was split between Contracts and IT.

8.1.1.3 Access Equipment

The requirement to hire Mobile Elevated Work Platforms (MEWPs) for the weather station installations was not anticipated at the start of the project.

8.1.2 IT

The £77,952 (+40%) variance in the forecasted and actual expenditure under IT was a result of the following elements:

8.1.2.1 Communications Infrastructure

As outlined in 8.1.1.2 there was a requirement for an additional four meteorological stations that included additional costs for their communication modules. As a result, the communication expenditure was approximately 50% higher than anticipated.

8.1.2.2 Security

The initial forecast also included £10,000 for the integration of the PowerOn client, Nortech iHost server in line with SP Energy Networks' IT Security policy and utilising existing communication networks. In hindsight this provision was significantly underestimated with the actual expenditure being closer to £35,000.

8.1.2.3 Development of RTTR in PowerOn Fusion

The largest element of IT expenditure was the fixed price contract was agreed with GE to deliver the TSE RTTR algorithm in a standalone PowerOn client in St Asaph Grid. This approach proved successful and ensured SP Energy Networks' expenditure was exactly the same as the initial forecast.

8.1.3 Labour

There was a £50,695 variance in SP Energy Networks' forecasted and actual expenditure. This variance was a result of the contribution of SP Energy Networks' project management and field staff being under estimated at the project's inception. Specifically, the project required additional SP Energy Networks Project Management to ensure the installation of the RTTR scheme was compliant with SP Energy Networks' policies and existing infrastructure. The requirement to work at height for each Grid Substation and Tower based weather station installation resulted in a substantially higher involvement from SP Energy Networks' field staff and Senior Authorised Persons (SAPs). As well as the installation activities there was also SP Energy Networks field staff / SAP involvement in the maintenance and repair of the weather stations and their associated communication infrastructure.

8.1.4 Materials

Although a marginal amount there was a necessity for stores materials to facilitate the weather station installations that was not included in the original forecast.

8.1.5 Legal

As with Materials there was a small amount of expenditure required under this category for the review of the contracts placed with the project partners.

8.2 Variance in Benefits

The previous R&D project reported the range of theoretical average uplifts that could be achieved through deployment of overhead line RTTR systems as 1.70 to 2.53 times the static summer rating. Furthermore, the additional annual energy yield from distributed generation that could potentially be accommodated through deployment of an RTTR was found to be 20 – 54% for the cases considered.

This LCNF project has built on the R&D project to establish the practical exploitable headroom that could be unlocked through a wide-scale deployment of RTTR systems. In this case, it was found that the average uplifts ranged from 1.24 to 1.55 times the static summer rating. The potential average additional annual energy yield ranged from 10% - 44% for the circuits considered.

The practical exploitable headroom and energy yields values are lower than the theoretical values. This is because the RTTR system deployed in the LCNF project takes into account constraints such as cable ratings and protection equipment ratings. For business acceptance, safety margins were introduced and estimates on the side of caution were refined, in comparison to the R&D project. Furthermore, the RTTR system was deployed in the LCNF project on an electrical network that is routed over a more varied terrain, which can be expected to affect the benefits accrued.

Prior to the project commencing, SP Energy Networks' only point of reference for the expected performance of the RTTR scheme was from the University of Durham TSB / IFI funded trial 'Active Management of Distributed Generators Based on Component Thermal Properties'. Figure 8-1 below provides an overview of the former project's results and the theoretical uplifts achieved over the course of 12 months.

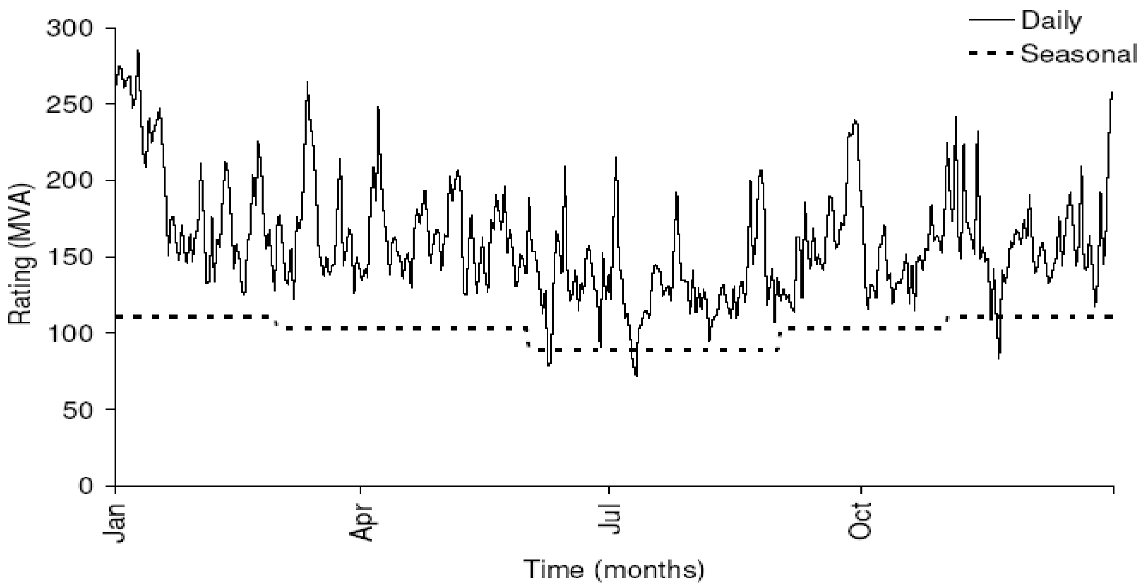

Figure 8-2 Real-time thermal ratings from the TSB / IFI project

The LCNF project's uplifts have been significant and in line with SP Energy Networks' aspirations. However, the reported results are lower than those achieved in the previous R&D project. This is attributed to the practicalities of implementation of the real scheme and its variance to the theoretical approach previously used, in particular:

- **Granularity** – the previous project established results using a daily average RTTR, whereas this project utilised RTTR values generated every five minutes and therefore captured a much higher variance in rating;
- **Coverage** – this project covered a substantially larger area of the network, which included a greater variance in ground roughness, altitude, direction and construction;
- **Meteorological** – the projects were carried out several years apart and as such were exposed to different weather conditions. Whilst the conditions average out over the course of 12 months there might be significant seasonal variation, for example the spring of 2013 was one of the coldest on record.

9 Lessons Learnt for Future Projects

Key learning points in deploying RTTR systems:

1. The importance of incorporating graceful degradation algorithms within the monitoring and control system to deal with equipment failure, communications interruptions and erroneous data;
2. Balance of centralised versus distributed intelligence and using distributed intelligence to report back information (not just data);
3. Use of multiple vendors for equipment supplies.

Recommendations for other projects:

1. The reliability of communications systems should not be taken for granted and should not be assumed to be 100%, particularly with GPRS systems;
2. Inclusion of end-to-end system diagnostics so that sources of error (equipment outages, communications outages and data outages) can be identified and pinpointed immediately, triggering remedial actions within suitable timescales;
3. Budgeting for whole project lifecycle (TotEx: CapEx, OpEx, decommissioning) and incorporation of 'spare' equipment in budgets.

9.1 Summary of Learning

This section provides key learning that resulted from the project. The learning has been categorised as that pertaining to RTTR system deployments, learning outcomes which are transferrable to other innovation projects and other learning outcomes from the project that have merit in being reported.

9.1.1 Key Learning Points in Deploying RTTR Systems

1. The importance of incorporating graceful degradation algorithms within the monitoring and control system to deal with equipment failure, communications interruptions and erroneous data;
2. Use of multiple vendors for equipment supplies;
3. Balance of centralised versus distributed intelligence and using distributed intelligence to report back information (not just data).

9.1.2 Recommendations for Other Projects

1. The reliability of communications systems should not be taken for granted and assumed to be 100%, particularly with GPRS systems;
2. Inclusion of end-to-end system diagnostics so that the source of error can be identified and pinpointed immediately;
3. Budgeting for whole project lifecycle (TotEx: CapEx, OpEx, decommissioning) and incorporation of IT, field staff, 'spare' equipment in budgets.

9.1.3 Summary of Other Learning Points

The other learning points that resulted from this project were:

- Factory acceptance tests (FAT) and site acceptance tests (SAT) proved invaluable for testing the end-to-end functionality of the system;
- Following the first substation installation, wiring diagrams were included in all the other junction boxes of the RTTR system to provide a point of reference for future maintenance operations;
- It was found that the small wiring of weather stations was a time-consuming process when carried out at height and led to erroneous connections. The installation process was modified to carry out small wiring operations on the ground, wherever practical;
- GPRS communications performed with sufficient reliability for the RTTR system proof-of-concept. However, the strength of the communications signal varied from site to site and there was a requirement to retrofit signal booster equipment at two sites. In future RTTR deployments, GPRS is likely to be superseded by more reliable systems such as meshed radio communications;
- Weather stations (in particular, ultrasonic wind sensors) reported erroneous signals due to snow and heavy rainfall. This is because the snow and rain droplets distort the ultrasonic signal. On the limited number of occasions where this phenomenon occurs, the temporary glitches can be detected and corrected through data conditioning techniques. However, the wind sensors performed well across the range of wind speeds that occurred during the twelve-month trial period and gave a particularly good level of granularity for wind speeds below 1 m/s.

SP Energy Networks will ensure that the wider lessons learnt in this project will be acted on in future projects by disseminating the report and project outcomes widely within the business. In particular, presentations on the lessons learnt have already been given to the Network Development team and key stakeholders for future projects were invited to attend the RTTR system dissemination event on 8th August 2013. Furthermore, SP Energy Networks has recently appointed a Knowledge Transfer Lead within its business to ensure that the learning of innovation projects is shared with internal and external stakeholders in a rigorous and robust way.

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

The following recommendations are made on how the outcome of the project can be exploited further:

1. Outcomes have fed into SP Energy Networks' RTTR business adoption strategy;
2. For the facilitation of wind farm connections;
3. Network reinforcement avoidance / deferral;
4. RTTR system is transferrable to other DNOs;
5. Data could be used for research purposes;
6. RTTR systems can be combined with ANM to capture the benefits of rating uplifts.

9.2.1 System Further Developments

The following work is planned to develop the RTTR system further: (i) temperature sensor deployment, followed by further validation; (ii) development and deployment of a graceful degradation algorithm; (iii) forecasting RTTRs (up to eight hours ahead for the emergency return to service plan); (iv) quantification of uplifts in different seasons; (v) quantification of additional capacity to accommodate wind farm connections; (vi) design of an ANM scheme to control the power output of wind farms utilising the SCADA-based RTTR for each circuit; and (vii) exploring RTTRs for contingency (N-1 and N-2) operation.

At this stage, system developments (i) – (v) will be implemented in SP Energy Networks' Tier 2 project "Flexible Networks for a Low Carbon Future". This will result in suitability assessments of the application to RTTR systems to 33kV networks. System development (vi) will build upon learning from the Tier 2 "ARC" project. Moreover, there are plans to trial the application of RTTRs to Scottish Power's transmission system. However, the funding mechanism for this work has not yet been specified.

9.3 Discovery of Significant Problems with the Trialled RTTR Method

The following significant problems were encountered with the trialled RTTR Method:

9.3.1 Reliability of Telecoms

Single point-to-point GPRS telecommunication infrastructure was adequate for trialling and demonstration purposes but was found to be unreliable at times. Therefore it is recommended that single point-to-point communication systems are avoided and other forms of telecommunication are considered as alternatives to GPRS. Furthermore, the dependency of the system on telecoms can be reduced through the development and deployment of graceful degradation algorithms, as illustrated in Section 7.

9.3.2 Tower-based Weather Stations

Considering the tower-based weather stations, a trade-off exists between the size (and hence weight) of the battery and its capacity to supply power for periods of low wind speed and low solar radiation. Tower-based weather stations provide a significant benefit to the RTTR system in terms of coverage. Therefore it is recommended that any DNO looking to deploy this method should purchase spare batteries and develop a system with overhead line staff to switch the batteries when low power signals are detected.

9.4 Deployment of RTTR on a Large Scale in the Future

There are planned implementations of the RTTR system at other voltage levels such as 33kV (through SP Energy Networks' LCNF Tier-2 project, Flexible Networks for a Low Carbon Future) and 275kV (potentially through one of the innovation mechanisms under RIIO).

9.5 Effectiveness of Contractual Methods

9.5.1 Contracts with generation and / or demand customers

This project did not involve any contractual methods with generation or demand customers.

9.5.2 Contracts with Project Partners

The contracts with project partners worked successfully. Parsons Brinckerhoff was employed on a Time and Expense basis for consultancy service provision. Equipment suppliers were contracted on a milestone payment basis.

10 Planned Implementation

The following work is planned to develop the real-time thermal rating system further: (i) temperature sensor deployment, followed by further validation; (ii) development and deployment of a graceful degradation algorithm; (iii) forecasting real-time thermal ratings (up to 8 hours ahead for the emergency return to service plan); (iv) quantification of uplifts in different seasons; (v) quantification of additional capacity to accommodate wind farm connections; (vi) design of an ANM scheme to control the power output of wind farms utilising the SCADA-based RTTR for each circuit; and (vii) exploring RTTRs for contingency (N-1 and N-2) operation.

10.1 Summary

This project has given SP Energy Networks confidence that there are significant rating uplifts achievable through RTTR and that such schemes could be utilised to facilitate the connection of onshore wind farms. It is SP Energy Networks' intention to work towards integrating RTTR-based connections into the business whilst exploring the operational benefits that can be introduced by RTTRs. However, prior to the adoption of RTTR based connections and / or operational practices there are several outstanding actions to be undertaken by SP Energy Networks and these are outlined in the subsequent sections.

10.2 Further Analysis and Development of TSE RTTR

Over the course of the last three years SP Energy Networks and the project partners have put significant effort into developing the TSE RTTR approach and specifically the algorithms built into PowerOn. However, whilst the system has delivered everything it was intended to, the live system has highlighted several areas for improvement necessary prior to adoption.

- **Graceful degradation** – as detailed earlier in the report graceful degradation will be imperative to ensure the performance of the RTTR scheme (and ultimately the network security). As a result of this improvements to the present graceful degradation approach built into the scheme have been identified and are intended to be introduced in follow on activities outside of the project;

- **Integration of sensors** – the TSE approach to RTTR requires validation through distributed sensors on the network prior to the system being adopted;

- **Forecasting -** prior to the use of RTTRs within an operational capacity i.e. during outages, an RTTR forecasting element will need to be developed to provide the control engineers with a highly probable minimum RTTR for at least eight hours. The application of existing and future academic research into this element will be considered.

10.3 Business Case for RTTR Systems

10.3.1 Introduction

An indicative financial evaluation has been carried out to compare the costs of increasing the capacity of a 10km 132kV overhead line by using two approaches (RTTR or Business as Usual (BaU)) across three different scenarios. The BaU approach comprises either reinforcing the line or building an additional line.

The unit costs were obtained from the data and supplier indicative quotations, provided to SP Energy Networks. Where data was not obtainable, suitable assumptions based on previous experience and other projects have been proposed.

10.3.2 System Characteristics

The three scenarios that have been assessed and compared are given in Table 10-1.

Table 10-1 Description of scenarios

Scenario	BaU	RTTR
1	New 132kV double circuit	New 132kV single circuit + RTTR
2	Reinforcement (refurbishment) of existing 132kV single circuit	Existing 132kV single circuit + RTTR
3	Additional new line (parallel) to an existing 132kV single line circuit	Existing 132kV single circuit + RTTR

The following capacity uplifts have been assumed:

1. Reinforcing the network by refurbishing (replacement of the 'Lynx' conductor with 'Upas' conductor) will increase the capacity from 89 MVA to 176 MVA, based on the summer static rating;
2. Reinforcing the network by building a new line would double the capacity of the circuit (from 89 MVA to 178 MVA);
3. The RTTR system will deliver an uplift of 30%, based on the minimum average uplifts that resulted from this trial.

10.3.3 Methodology

This financial evaluation considers the present value (PV) of the expenditure (CapEx, O&M expenditure and decommissioning costs) related to the BaU and RTTR approaches. It does not consider the revenue streams from the deployment of RTTR systems or BaU approaches. The present value (PV) of the expenditure has been calculated by applying a discount rate of 6.9% and taking into account the different life expectancies of the equipment. (For example, overhead line assets are assumed to have a 48-year lifetime, whereas the RTTR system has a 20 lifetime, which is in line with prospective wind farm developments). Moreover, O&M costs take place at different intervals depending on the equipment considered and, for this financial evaluation, it is assumed that O&M works will take place at the beginning of each calendar year.

10.3.3.1 Overhead Line Costs

For the scenarios where new circuits are required, these will be 132kV and either single circuit or double circuit construction. Descriptions are given in Table 10-2.

Table 10-2 Overhead Line Circuit Types Considered

Voltage (kV)	Circuit Code	Circuit Description	Rating (A)	Rating (MVA)
132	A	132kV Single Circuit Steel with UPAS Conductor	769.8	176
	B	132kV Double Circuit Steel Tower with UPAS Conductor	1539.6	352

Where reinforcement of the overhead line is required, the following cost categories have been included:

1. Switchgear equipment;
2. Protection equipment;
3. Overhead line construction;
4. Tower construction (for newly built infrastructure).

The indicative unit costs of the capital investment include materials and labour and are £405,000/km and £125,000/km for new build and refurbishment approaches respectively.

The O&M costs for the overhead lines are taken into account for all scenarios. Each element has different maintenance and refurbishment frequencies which have been combined to calculate the lifetime O&M costs. These have then been divided by the life expectancy of the equipment to create the indicative annual expenditure figure of £10,250/per circuit.

10.3.3.2 RTTR System Costs

The RTTR system will have units installed in substations and overhead line towers. It is assumed that two substation-based weather stations are installed at each end of the 10 km line and one tower-based weather station is installed at a point along the length of the overhead line to provide redundancy.

The RTTR system is formed of the following elements:

1. Substation RTTR Installation (Weather station and micro RTU);
2. Tower RTTR Installation:
   a. Weather station and micro RTU;
   b. Tower mounting;
   c. Wind turbine and solar PV;
3. Line temperature and current sensors;
4. Master RTU;
5. RTTR Server;
6. RTTR licence.

The indicative CapEX cost of the RTTR system is £190,300 (including materials and labour).

The indicative annual O&M cost of the RTTR system is £3,825 / annum.

10.3.4 Results

The summary of the initial investment, annual O&M costs and present value of lifetime expenditure for the three scenarios are given in Table 10-3.

Table 10-3 Financial Summary

		Description	Initial Investment	O&M Costs P/A	PV of TotEx
Scenario 1	BaU	New 132kV double circuit	£7,200,000	£ 20,500	£7,504,691
	RTTR	New 132kV single circuit + RTTR	£4,889,900	£ 14,075	£5,129,232
Scenario 2	BaU	Reinforcement (refurbishment) of existing 132kV single circuit	£2,857,143	£ 10,250	£3,009,488
	RTTR	Existing 132kV single circuit + RTTR	£190,300	£ 14,075	£433,988
Scenario 3	BaU	Additional new line (parallel) to an existing 132kV single line circuit	£4,700,000	£ 20,500	£5,004,691
	RTTR	Existing 132kV single circuit + RTTR	£ 190,300	£ 14,075	£ 433,988

Scenario 1 presents the highest initial Investment of all scenarios. This is expected as a new double circuit line is required for the BaU solution and a new single line with RTTR is required for the RTTR solution. Annual O&M costs are £20,500 for the BaU solution, approximately £6,400 higher than the RTTR solution (due to the BaU solution requirement to maintain two circuits). Since both initial investment and O&M costs are higher for the BaU solution, the PV of the cost of the RTTR solution is lower and could be more favourable. However, building a double circuit increases the capacity of the line to 352 MVA and this could provide unconstrained firm capacity for generation connections when compared to the RTTR solution. Considering Scenario 2, the BaU and RTTR system approaches both have lower initial investment costs when compared to Scenario 1. Since the RTTR system is retrofitted to an existing circuit, the initial investment is significantly lower than the BaU approach. However, the RTTR system approach is more labour-intensive when considering ongoing O&M costs. Considering Scenario 3, the RTTR solution is the same as for Scenario 2. The BaU solution differs as a new line is required. Therefore, the initial investment and O&M costs both increase compared to Scenario 2.

10.3.5 Conclusions

RTTR solutions are more attractive because of their potential to unlock latent power flow capacity in electricity systems, avoiding or deferring the need network reinforcement and overcoming environmental barriers. RTTR systems have lower upfront costs and they also have lower annual maintenance costs when compared to the construction of double circuit lines for network reinforcement. However, the O&M costs are higher if they are compared to replacement of an existing line with a higher-rated conductor.

The net present value (NPV) calculations demonstrate that there is a compelling argument to deploy RTTR systems, for the cases where capital investment and on-going maintenance costs associated with network reinforcement are high. However, the following questions (as examples) still need to be addressed, which influence the business case and ultimate deployment decision:

- Who should pay for the monitoring and RTTR system equipment? (For example, the customer, the DNO or both parties).
- How are connection applications assessed and costs attributed to customers with a dynamic rather than static line capacity?

The business case analysis could be extended further to take into account the revenue streams for DNOs associated with the different solutions, providing a more comprehensive net present value (NPV) evaluation.

Therefore, there is more work to be done to increase the confidence of the business prior to the roll out of RTTR across 132kV networks. However, SP Energy Networks is confident that RTTR systems will be offered to future customers. In order to facilitate this, SP Energy Networks is convening a business adoption team to decide on priorities for the roll out of RTTR systems. The selection criteria in deploying RTTR is expected to be driven by a need case, such as a generation connection which could be accommodated more quickly and cheaply through an RTTR system deployment. Initially, RTTR system deployments may be connection driven, rather than reinforcement driven. SP Energy Networks plans to use a staged approach, firstly by deploying RTTR systems on single spur circuits and then, as the risks are reduced, deploying RTTR systems on interconnector circuits.

At this stage there are no immediate plans to avoid or defer reinforcement of the 132kV network based on the outcomes of this project. This is because the urgency of one of the drivers for the project has reduced (consents to build more than 200 MW prospective wind generation in North Wales have been delayed). Using an incremental deployment approach, it is anticipated that RTTR systems will be used for single-circuit connections to generation customers in the first instance followed by the up-rating of interconnector circuits (and utilising RTTR forecasts) at a later stage.

10.4 De-risking the Implementation of Real-time Thermal Ratings

The RTTR system development process is described below with a discussion of the cautious approach to mitigate risks and uncertainties, in order to demonstrate the same level of risk (or, indeed reduced risk) when compared to the static ratings utilised at present in the UK.

10.4.1 Real-time Thermal Rating System Risks

Key risks were identified in the RTTR system design phase through a failure modes and effects analysis (FMEA). For each failure mode, as shown in Table 10-4, the pre-mitigation risk, R, has been quantified through multiplying the probability of occurrence, P (1=low, 5=high) by the magnitude of impact if the failure mode occurred in practice, I (1=low, 5=high). The residual (post-mitigation) probability, impact and risk are given in **bold**.

In addition to the risks identified in Table 10-4, there are also RTTR system uncertainties that need to be considered:

<u>Accuracy of instrumentation</u>: In order to reduce uncertainties and systematic errors relating to the accuracy of monitoring instrumentation, a correction factor is applied to each sensor to ensure that the most conservative RTTR is calculated. The correction factor is selected using suppliers'

equipment specification sheets. On this basis, the wind speed value is reduced, the wind direction value brings the angle of incidence closer to parallel, the ambient temperature value is increased and the solar radiation value is increased.

Drift of signals with time: In order to mitigate the drift of monitoring signals with time, the system is recalibrated after a maximum period of two years.

Table 10-4: FMEA of RTTR system

Failure mode	Effect	P	I	R
Information technology / Telecommunications failure	Reduction in thermal visibility	4 ↓ **4**	5 ↓ **1**	20 ↓ **4**
Too many additional planned outages required to install and maintain system	Reduction in power system reliability and security of supply to customers	3 ↓ **2**	5 ↓ **2**	15 ↓ **4**
Uncontrolled thermal excursion	Conductor degradation and failure	3 ↓ **3**	5 ↓ **1**	15 ↓ **3**
Lack of sufficient thermal visibility of overhead line network after RTTR system deployment	DNO business does not have confidence to adopt system	3 ↓ **1**	5 ↓ **3**	15 ↓ **3**
RTTR system is too expensive (comparative investment with network reinforcement)	RTTR system not adopted on an economic basis	2 ↓ **1**	5 ↓ **3**	10 ↓ **3**
Change in line construction, land use and vegetation growing near conductors	Conductor clearance infringement	4 ↓ **3**	2 ↓ **1**	8 ↓ **3**

10.4.2 Mitigation and Benefits

In order to mitigate the above mentioned risks, SP Energy Networks' RTTR system utilises a thermal state estimation with integrated sensors approach. This cost-effective approach uses a meshed network of weather stations together with a detailed geographical model that allows the weather conditions at every span within the 90km overhead line network to be interpolated. The RTTR and operating temperature of each span of the overhead line network is calculated. The system identifies the span within each circuit that has the lowest rating and this is used to provide the rating for the entire circuit. The operating conditions of the identified critical spans are validated against a limited number of conductor temperature sensors, carefully selected to minimise the number and duration of outages required for equipment installation.

By modelling the entire system, the DNO is provided with complete thermal visibility of the overhead line network. The meshing of weather stations allows the system to degrade gracefully, thereby making increasingly conservative estimates of the overhead line thermal ratings as an increasing number of input signals are lost. Furthermore, the integration of the RTTR system with an ANM system mitigates the risk of excessive thermal excursions at times of low thermal rating through power flow control techniques. This functionality is vital for the future integration of low carbon generation sources such as wind farms.

10.5 Development of an RTTR-based ANM Scheme

The development of an operationally compliant and business adopted ANM scheme is a prerequisite for the role out of RTTR based connection offers to wind farms. As such the acceptance and roll out of RTTRs will be tied to the success of SP Energy Networks' adoption of ANM schemes currently on trial / in development.

10.6 Alternative RTTR Approaches

As outlined in Section 4.4, prior to the project's creation a detailed Literature Review was undertaken to analyse the available RTTR approaches available at that time. Ultimately the decision was made to pursue the TSE approach as SP Energy Networks had strong awareness of the approach and SP Energy Networks favoured its minimal outage requirement.

In the subsequent three years there have been some notable developments in RTTR technology and a significant increase in the number of technologies that are commercially available. Prior to the development of future RTTR adoption plans it is recommended that SP Energy Networks analyses the present RTTR products and services available, reviews the lessons learnt and outcomes from other LCNF projects, and identifies the approach most beneficial to the network and its customers.

11 Facilitate Replication

- The knowledge required to replicate this project is contained within this report and the publications listed in Appendix B.
- The products required to replicate the RTTR system can be categorised as (i) weather stations; (ii) monitoring equipment; (iii) communications equipment; and (iv) information technology equipment.
- The services required to replicate the RTTR system may be delivered by a consortium, which includes: (i) the DNO (or consultancy acting on the DNO's behalf); (ii) the weather station / monitoring equipment supplier; (iii) the communication solution provider; and (iv) the information technology system supplier.

It is recommended that any DNO looking to replicate this Method of RTTR system deployment should use the category guidelines as given in the Facilitate Replication section of this report for building up capital expenditure and O&M expenditure estimates.

In keeping with the Objectives of the Low Carbon Networks Fund, the following points of contact are available to provide further details on the RTTR system replication:

i. Geoff Murphy, SP Energy Networks (Geoff.Murphy@sppowersystems.com);
ii. Samuel Jupe, Parsons Brinckerhoff (JupeS@pbworld.com);
iii. Derek Syme, GE Digital (Derek.Syme@ge.com);
iv. Simon Hodgson, Nortech Management Limited (Simon.Hodgson@nortechonline.co.uk);
v. Jolyon Wicks, Skye Instruments (Jolyon@skyeinstruments.com).

The following IPR, knowledge, data, products and services are required by other DNOs to replicate the RTTR system or configure the RTTR system to account for additional or modified overhead lines:

11.1 Knowledge Required to Replicate the RTTR System

The knowledge required to replicate the RTTR system and deployment methodology is outlined below:

- RTTR system design methodology;
- RTTR system providers;
- Weather station providers;
- RTU / telecoms;
- Papers / presentations;
- DNO stakeholder map for business adoption.

In order to disseminate the learning from the project to other DNOs and other interested parties, a number of papers have been published throughout the course of the project at international conferences. A list of key publications is given in Sections 11.1.1 and 11.1.2, and full list of publications and presentations is provided in Appendix B1.

Moreover, a dedicated dissemination event was held on 8 August 2013, which was attended by representatives from every other DNO as well as other interested parties (EA Technology, GE Energy, National Grid, Nortech Management Limited, Skye Instruments Ltd, University of Newcastle and University of Strathclyde). The presentations, discussions and feedback summary from the event are included in Appendix B2.

11.1.1 Conference Publications

- SCE Jupe, M Bartlett, K Jackson and PC Taylor: "Facilitating the Connection of Wind-Based Generation through Real-Time Thermal Ratings", in Proc. 9th International Workshop on Large-scale Wind Integration, Quebec, October 2010.
- SCE Jupe, MG Bartlett and KT Jackson: "Dynamic Thermal Ratings: The State of the Art", in Proc. 21st International Conference on Electricity Distribution, Paper 0918, Frankfurt, June 2011.
- SCE Jupe, D Kadar, G Murphy, MG Bartlett and KT Jackson: "Application of a Real-time Thermal Rating System for a 132 kV Distribution Network", in Proc. 2nd IEEE PES European Conference and Exhibition on Innovative Smart Grid Technologies, Manchester, December 2011.
- SCE Jupe, G Murphy and A Khajeh Kazerooni: "De-risking the implementation of Real-time Thermal Ratings", in Proc. 22nd International Conference on Electricity Distribution", Paper 1106, Stockholm, June 2013.

11.1.2 On-line publications

- Scottish Power Energy Networks "Dynamic Thermal Ratings Brochure", 2012, on-line at: www.spenergynetworks.com/innovation
- Scottish Power Energy Networks "Implementation of Real-time Thermal Ratings, Quarterly Report: Q4 2012", 2013, on-line at: www.spenergynetworks.com/innovation

11.2 Summary of Intellectual Property Rights

A summary of background IPR and relevant foreground IPR is given in Table 11-1.

Table 11-1 IPR

Background IPR	Relevant foreground IPR
Durham University algorithm	Weather station location methodology
PowerOn Fusion DMS/OMS/SCADA product, including DTR module	Method statements
PowerOn Fusion documentation	Weather station data
PowerOn Fusion DTR software licence	RTTR datasets
PowerOn Fusion DTR Test Specification	RTTR algorithm functional specification
PowerOn Fusion DTR Data Load Tool	RTTR algorithm data requirements
Envoy RTU	Papers and presentations (as listed in Appendix B)
iHost SCADA system	
Envoy PPP, IP over serial link	
Envoy Min/Max/Average and Standard Deviation calculation	
Envoy Weather Station Monitoring cabinet design for off-grid applications	
Improvements to iHost and Envoy DNP3.0 support	

11.3 Data Required to Replicate the RTTR System

The datasets required to replicate the RTTR system are outlined below:

- Electrical and geographic data to model each line segment, provided in Microsoft Excel file format by the DNO.

A number of datasets, as given in Appendix I, have been created as an output of this project:

- Weather data (wind speed, wind direction, ambient temperature, solar radiation) for ten meteorological station installations;
- RTTR data for eight 132kV overhead line circuits.

11.4 Products Required to Replicate the RTTR System

The products required to replicate the RTTR system can be categorised as (i) weather stations; (ii) monitoring equipment; (iii) communications equipment; and (iv) information technology equipment. These product categories are described in more detail in the following sections:

11.4.1 Weather Stations

- Substation-based;
- Tower-mounted (weather station, mast, mounting brackets, small wiring).

11.4.2 Monitoring Equipment

- Temperature;
- Tension;
- Sag;
- Thermal imaging

11.4.3 Communications Equipment

- Hardwired substation-based;
- Wireless tower-based (RTU cabinet, RTU, SIM card (for GPRS data transfer), battery, solar panel, micro wind turbine, power regulators, power cables).

11.4.4 Information Technology

- System running GE PowerOn v5, with suitable licence agreement for RTTR module for each circuit being modelled;
- Suitable PowerOn FEP to interface to system providing weather data, may be a dedicated FEP or an existing PowerOn FEP;
- Weather data provided as 5-minute average values at synchronised intervals via a protocol supported by the PowerOn FEP;
- Suitable PowerOn symbology for weather stations and RTTR summary pages, these can be developed by the DNOs own team or with services provided by GE Energy;
- Configuration of SCADA links for each weather station symbol, this can be implemented by the DNO or with services provided by GE Energy;
- Site acceptance testing with DNO, supplier of weather station hardware and GE Energy.

11.5 Services Required to Replicate the RTTR System

The services required to replicate the RTTR system may be delivered by a consortium, which includes: (i) the DNO (or consultancy acting on the DNO's behalf); (ii) the weather station / monitoring equipment supplier; (iii) the communication solution provider; and (iv) the information technology system supplier. The services, which could be provided by the various members of the consortium, are provided below. Depending on the policy of the DNO, these services could be provided in-house.

11.5.1 DNO

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

- Project management;
- System design:
    - Weather station location specifications;
    - Monitoring equipment location specifications;
    - GPRS survey;
    - CBA;
    - Overhead line thermal survey;
    - Overhead line equipment survey;
- Equipment procurement;

- Equipment storage facility;
- Fitting teams for substation weather station installation / maintenance / decommissioning;
- Overhead lines team for tower-based weather station installation / maintenance / decommissioning;

11.5.2 Consultant

The following services could be provided by a consultant acting on the DNO's behalf for RTTR system replication:

- Project management, as outlined in Section 11.4.1;
- System design, as outlined in Section 11.4.1;
- Support with equipment procurement, as outlined in Section 11.4.1;
- Witnessing and supporting equipment installation;
- Training.

11.5.3 Weather Station / Conductor Monitoring Equipment provider

The following services could be provided by the weather station / conductor monitoring equipment provider:

- Post-commissioning system support, for example training, maintenance and diagnostic services.

11.5.4 Communications Provider

The following services could be provided by the communications equipment provider:

- Post-commissioning system support, for example maintenance and diagnostic services.

11.5.5 Information Technology Provider

The following services could be provided by the information technology equipment provider:

- Post-commissioning system support, for example maintenance and diagnostic services.

11.6 Recommendations

11.6.1 Cost Estimates

It is recommended that any DNO looking to replicate this Method of RTTR system deployment should use the information above as category guidelines for building up capital expenditure and O&M expenditure estimates.

11.6.2 Summary of Points of Contact

In keeping with the Objectives of the Low Carbon Networks Fund, the following points of contact are available to provide further details on the RTTR system replication:

1. Geoff Murphy, SP Energy Networks (Geoff.Murphy@sppowersystems.com);
2. Samuel Jupe, Parsons Brinckerhoff (JupeS@pbworld.com);
3. Derek Syme, GE Digital (Derek.Syme@ge.com);
4. Simon Hodgson, Nortech Management Limited (Simon.Hodgson@nortechonline.co.uk);
5. Jolyon Wicks, Skye Instruments (Jolyon@skyeinstruments.com).

Appendices

Appendix A: LCNF First Tier Registration Pro-forma

Appendix A1: Original Registration Pro-forma

Appendix A2: Revised Registration Pro-forma

Appendix B: Summary of Dissemination Activities

Appendix B1: Papers and Publications

Appendix B2: Dissemination Workshop

Appendix B3: Questions and Answers

Appendix C: RTTR Functional Specification

Appendix D: RTTR Data Requirements Specification

Appendix E: Equipment Specifications

Appendix E1: Weather Station Specification

Appendix E2: RTU Specification

Appendix F: Method Statements

Appendix F1: Method Statement for Substation Weather Station Installation

Appendix F2: Method statement for Tower-mounted Weather Station Installation

Appendix G: Summary Data Results for 12 Months of Operation

Appendix H: Quarterly Report: Q4 2012

Appendix I: Datasets